THE

# DESIGN AND CONSTRUCTION OF HARBOURS

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January 31/87

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OF

# HARBOURS

## A TREATISE ON MARITIME ENGINEERING

BY

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*THIRD EDITION.*

EDINBURGH
ADAM AND CHARLES BLACK
MDCCCLXXXVI

*Printed by* R. & R. CLARK, *Edinburgh.*

## PREFACE TO THIRD EDITION.

HAVING been informed by the publishers that a new edition of this work was frequently asked for, I have revised it for republication.

I have again to thank my professional brethren for the assistance which they have rendered.

84 GEORGE STREET,
EDINBURGH, *January* 1886.

# PREFACE TO FIRST EDITION.

THE following pages are a reprint, with many additions, of the article "Harbours," in the last edition of the *Encyclopædia Britannica*. The late Professor Hosking, of the London University, proposed to republish that Article, along with several others, from the *Encyclopædia*, as an independent Treatise on Civil Engineering and the Constructive Sciences; and it was accordingly revised, with the intention of its appearing as one of the proposed series. Owing to the death of Professor Hosking that work was not proceeded with, and the article is now published by itself in a separate form.

I have endeavoured to make this volume a useful contribution to Maritime Engineering, by introducing into it, as largely as possible, the results of actual practice. In requesting a measure of indulgence for the insertion of matter which is familiar to the experienced practitioner, I would remind the reader of the necessarily comprehensive character of an *Encyclopædia* article; while, for imperfections and undue

abbreviations, I can only urge my desire to enlarge upon those branches of which I happened to have had most personal experience, rather than to deal too much with subjects at second hand. The reader will, however, notice how much I am indebted to several of my engineering friends, and also to the excellent *Cours de Construction—Ouvrages Hydrauliques des Ports de Mer*, by M. Minard.

EDINBURGH, *March* 1864.

# CONTENTS.

## CHAPTER I.

GENERAL DEFINITIONS OF DIFFERENT KINDS OF HARBOURS—INTERIOR WORKS—EXTERIOR WORKS, ETC.



## CHAPTER II.

GEOLOGICAL AND OTHER PHYSICAL FEATURES.



## CHAPTER III.

GENERATION OF WAVES.

## CHAPTER IV.

### FORCE OF THE WAVES.



## CHAPTER V.

### CONDITIONS WHICH AFFECT THE FORCE OF WAVES.

## CHAPTER VI.

### DESIGN OF PROFILE, ETC., OF HARBOURS IN DEEP WATER.



## CHAPTER VII.

### DESIGN OF PROFILE, ETC., FOR TIDAL HARBOURS.



## CHAPTER VIII.

### DESIGN OF GROUND-PLAN OF HARBOURS.

## CHAPTER IX.

### DOCKS, TIDE-BASINS, LOCKS, GRAVING-DOCKS, SLIPS, ETC.



## CHAPTER X.

### MATERIALS, KINDS OF MASONRY, IMPLEMENTS, ETC.

## CHAPTER XI.

### ON THE EFFICACY OF TIDE AND FRESH WATER IN PRESERVING THE OUTFALL OF HARBOURS AND RIVERS.



## CHAPTER XII.

### ON THE PRINCIPAL CAUSES OF SILTING IN ESTUARIES.

## CHAPTER XIII.

### MISCELLANEOUS SUBJECTS RELATING TO HARBOURS.

# CHAPTER I.

## GENERAL DEFINITIONS OF DIFFERENT KINDS OF HARBOURS—INTERIOR WORKS—EXTERIOR WORKS, ETC.

**1. Harbours of Refuge and Anchorage Breakwaters—2. Deep-water and Tidal Harbours for commercial purposes—3. Kanted or Curved Piers—4. Straight Pier—5. Quay or Wharf—Different Exposures require different kinds of Harbours—Requirements of a good Harbour—Technical Terms.**

ALL harbours may be classed either as havens for the protection of ships during storms, or as ports adapted for commercial purposes.

Of the first-mentioned class, or those which are called harbours of refuge, some are natural and some artificial. Many parts of the British coasts are amply provided with natural bays and creeks, while in other districts the accommodation and shelter have been entirely supplied by artificial means. Thus, great portions of Ireland and of the west coast of Scotland are plentifully provided with excellent deep-water bays and anchorages; while on the east and south-west shores of Britain there are few natural harbours. Cromarty Bay, described by Buchanan as "adversus omnes tempestates portus salutiferus ac certum perfugium,"[1] is 200 miles distant from the Firth of Forth, which is the nearest natural harbour to the south; and there are no fewer than 400

[1] *Rer. Scot. Hist.*, Auct. G. Buchanano, 1583.

miles between the Firth of Forth and the Thames, which may be considered as the next really unexceptionable place of refuge. On the west coast, there are about 200 miles between the nearest harbours of Milford and Loch Ryan. The construction of artificial places of refuge becomes, therefore, a very important matter in a country where every winter's list of shipwrecks and loss of life reminds us how much nature has left for art to accomplish. For the most perfect body of evidence regarding the ports of Britain, we cannot do better than refer to the volumes of *Reports by the Royal Tidal Harbours' Commission of* 1846, for the completeness of which the public is mainly indebted to the zeal of the late Admiral Washington, the indefatigable hydrographer to the Admiralty; and also to the "Return by Harbour Authorities, 1883," moved for by Mr. Marjoribanks, Chairman of the Harbours Accommodation Committee.

The designing of harbours constitutes confessedly one of the most difficult branches of civil engineering. In making such a design, the engineer, of course, avails himself of the information which is to be derived from past experience; but perfect identity, however, in the physical peculiarities of different localities, seldom, if ever, exists.

Mr. L. F. Vernon Harcourt, in his "Account of the Construction and Maintenance of the Harbour at Braye Bay, Alderney," remarks: "The difference in the force of the sea in different localities, positions, and depths, is probably far greater than is generally imagined. The force would be difficult to compute with accuracy; but its estimation is of the greatest importance in designing structures in the sea, and a comparison between the breakwaters at Alderney and at St. Catherine's Bay, Jersey, will best illustrate this.

The original designs for the breakwaters at Alderney and at St. Catherines were almost identical. Both were to be carried into about the same depth of water, and both sites were unsheltered by any projecting headland. The differences, as regards the tide and situation with respect to the adjacent coast, were rather in favour of the Alderney breakwater; the rise of tide at Jersey being double the rise at Alderney, and the breakwater at St. Catherines stretching more directly out to sea. Both were executed by the same contractors, under the direction of the same engineers, and they are only about thirty miles apart. The history, however, of their construction and maintenance, presents a remarkable contrast. . . . The total cost of the [Alderney] works of construction and maintenance, extending over a period of twenty-five years, amounts to £1,274,200, and of this sum £57,200 were expended in repairs of damages caused by the sea to finished and unfinished work. . . . The only damage of any importance that occurred [at St. Catherine's till 1871] happened in 1859, when some cracks appeared, and some stones were broken in the masonry of the head, owing to the unequal settlement of the superstructure on the rubble base. These damages were repaired at a cost of about £700, and the author believes that, from first to last the cost of maintenance has been under £1000."

So great indeed was the expense of maintaining the harbour at Alderney, on the other hand, that the works were at last altogether abandoned.

In order still further to illustrate the nature of the difficulties which beset the marine engineer, let us suppose that he is called upon to design works for the accommodation of shipping in a given locality. The questions which immediately

press on his attention are, *first,* What is the cheapest kind of design which is suitable for the place and sufficient for the class of shipping which has to be accommodated? and *second,* the question used to be, What are the smallest sizes of materials that are admissible in its construction? as on this the cost of the work used materially to depend. The all but universal adoption of concrete work has now, however, most materially changed matters, and led to the new question, How large must blocks of concrete be to preserve their equilibrium? Before considering how far it is possible to answer such questions as these, let us endeavour to define the different varieties of design into which all sorts of harbours may, with propriety, be resolved.

In the first place, they may be all classified under two main heads—viz. *Interior Works* and *Exterior Works.*

*Interior Works.*—The interior works are provided for the accommodation and repair of vessels. They consist of tide basins with or without gates—of wet docks with entrance locks—of graving (or dry) docks—patent slips—gridirons, etc., the three last mentioned being only for the reception of vessels requiring repairs. It is not proposed to enter upon any very detailed description of the inner works of harbours, as, from their situation, they are necessarily protected from heavy seas, and are consequently more nearly of the same character at different harbours than the exterior works, the nature of which must vary more or less with every locality.

*Exterior Works.*—The exterior works of harbours may be conveniently enough classified under the following five different designs—

## DIFFERENT CLASSES OF HARBOURS.

1*st*, *Harbours of Refuge and Anchorage Breakwaters*, consisting of one or more breakwaters, so arranged as to form a safe roadstead, which shall be easily accessible to the largest vessels in all states of the weather and tide. A breakwater forms a barrier either complete or partial to the progress of the waves, and is intended for sheltering the anchorage ground under its lee. It is not used for commercial traffic, as are piers or quays, and therefore a parapet is not necessarily required for preventing the waves from breaking over the top, although it may be useful as a protection against the wind.

2*d*, *Deep-water and Tidal Harbours for commercial purposes* (Fig. 1, *a* and *b*).—A harbour for commercial purposes is any arrangement of piers or breakwaters, or of both, which encloses and so tranquillises a sheet of water that vessels may be moored at the quay walls or wharves which form the inner sides of the piers. Where the coast-line lies open to a heavy sea it is often found necessary to make a compound or

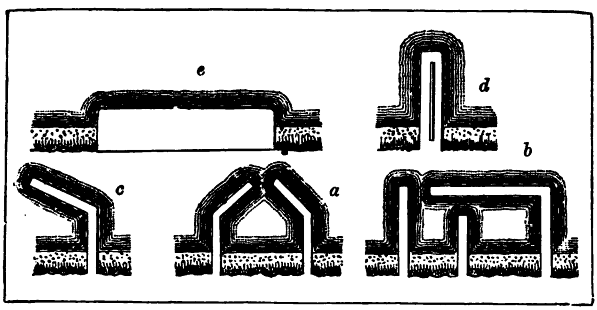


Fig. 1.

double harbour (Fig. 1, *b*). In such a case the entrance to the inner basin is situated within the sheltered area formed by the outer works.

*3d, Kanted or Curved Piers* (Fig. 1, *c*).—Where there is a single pier of this kind, vessels lie under the lee of the kant or kants, and the sheltered side of the pier is therefore finished as a quay. The pier may have a double kant, or cross-head, built at right angles to the main portion, so as to give the structure the form of the letter T; at one side or the other of which, according to the direction of the wind, vessels can always find some shelter. We propose to term the outer extremity of any single pier its *free end*, because there is an expanse of open sea all round it, in contradistinction to the outer end of a close harbour, where the sea-room is limited to the breadth of entrance, which is always kept as narrow as is consistent with the safe passage of vessels. Both extremities of all single insulated breakwaters are, of course, free ends, as are also the seaward ends of all single breakwaters which are connected with the land.

*4th, Straight Piers* (Fig. 1, *d*).—A straight pier generally projects at right angles to the coast-line, with a free end at its seaward extremity, and, unless when the wind blows right in upon the shore, a straight pier will always afford some shelter on its lee side. In order to get the full advantage of this kind of pier, both sides are sometimes finished as quay walls, and the parapet, if there be one, is built in the middle of the roadway, as at Granton in the Firth of Forth.

*5th, Quay or Wharf* (Fig. 1, *e*).—A quay wall or breast wall is usually built parallel to the line of shore. It affords no shelter of any kind, and the only advantage which it possesses is that of enabling vessels to load and unload

without their having to "beach," or, where the shores are steep, even to take the ground. The same object may also be effected by an open framework of timber or iron piles—by a suspension bridge, with a wharf at its outer end—or by a floating pier rising and falling with the tide, and connected with the shore by a bridge.

*Different Exposures require different kinds of Harbours.*—It will be observed that all the kinds of piers or harbours just enumerated differ materially from each other in the amount of shelter which they afford, and are therefore suitable for places having very different degrees of exposure. Now we find an almost infinite diversity in the height of waves when we pass along the coast from one part to another. In some places there are shores which lie open to the full fury of the ocean, while other parts of the same coast are protected in some directions by projecting headlands or islands or outlying reefs or sandbanks. Then, leaving the main coast, we have the shores and bays of narrow Sounds, the breadths of which vary at different places; and lastly, we have creeks so perfectly land-locked, as to afford naturally complete shelter in the worst weather. In some situations the foreshore is steep, affording sufficient depth for heavy waves not only to reach the beach, but to tear up rocks at levels far above the high-water line; while in others it is so flat and shallow as to form a natural breakwater for the protection of the coast. In some districts there are tides rising forty or fifty feet, in others not as many inches; and lastly, we have differences in the geological formation and in the tendency to deposit. Now, it is quite as bad engineering to adopt the unjustifiable policy of erecting, in sheltered seas, works that are heavy enough for the opén ocean; as, through an under-

estimated notion of the exposure, to fall into the opposite error of designing structures that are deficient in strength and efficiency. The very first step to be taken, therefore, is to select from the different classes of designs which have been enumerated, the one which is best adapted to the physical peculiarity of the situation. The engineer, in order to make this selection judiciously—keeping ever in view the essential elements of *stability, economy, safety of ingress and egress, and convenient despatch for the trade of the port*—must consider the following queries :—

*First,* Is the place so well sheltered naturally as to require no artifical protection of any kind, so that a quay without a parapet, or an open framework of timber, will be sufficient for vessels to lie alongside without risk of damage in all ordinary states of the weather? Examples of such quays may be found in rivers and creeks even where there is a considerable expanse of water, such as Greenock, Invergordon, and the like.

*Second,* Is the place situated in a Sound or Estuary, where the cross waves or those which come *endways* on the pier are small, owing to the estuary being narrow, and where the heaviest waves are those which assail the work on its sides, so that a straight pier will be sufficient? Of this Burntisland in the Firth of Forth is an example.

*Third,* Is it necessary to protect the berthage by means of a curved or kanted pier, as may be seen in a great variety of places where the sea is not very heavy?

*Fourth,* Is it necessary that a space of water should be enclosed between two piers inclined to each other till they nearly meet, and admitting (through the narrow entrance thus formed) only a small portion of the outside wave, which is afterwards reduced by expanding into the enclosed area?

Examples of this may be seen at Ramsgate, and very many other places on the coasts of Britain.

*Fifth,* Must we have recourse to what may be called a *compound harbour,* consisting of one harbour within another, where the outside waves are first reduced by expansion into the area of the outer or stilling harbour, after which a yet greater reduction is attained by a second expansion of a portion of the reduced wave into the area of the inner basin? Examples of such double harbours are common on all coasts which are much exposed.

*The Requirements of a good Harbour.*—After the engineer has satisfied himself as to the *general* character or class of design required,—which is undoubtedly the principal question to be settled, he must next consider the details. If the place be much exposed he must arrange the different parts of the work so as to produce a harbour which may be easily taken and left in stormy weather, without endangering the tranquillity of the internal area; for it is *the combination of the qualities of safe and easy entrance and exit, with a good "loose" and a smooth interior, which constitutes a good harbour.* Lastly, he must fix the width of the piers and height of the parapets, and assign the sizes and determine the arrangement of the constituent materials in such proportions as to ensure the stability of the whole structure.

What follows is an attempt to assist the engineer in the solution of some, at least, of these and other questions affecting the construction of harbours.

The local characteristics which at the outset demand our consideration are — 1st, The geological and other physical peculiarities of the shore; 2d, the exposure; 3d, the force of the waves due to the exposure; 4th, the strength, direction, and range of the tides; 5th, the depth of water of the bay or

sea in which the harbour is to be placed; 6th, the proximity of deep water to the pier itself, which, of course, depends on the slope of the foreshore; and 7th, the angle which the coast-line makes with the direction in which the heaviest waves come.

Before proceeding to consider some of these different subjects it may simplify matters to non-professional readers, or others who are beginning to study the subject, to denote, as shown in Figs. 2 and 3 on the opposite page, a few of the technical names of the different parts of a pier, which will be very frequently employed as we proceed.

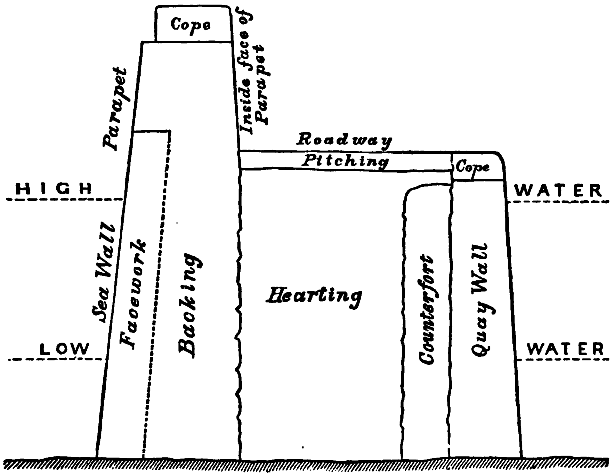

Cope
Inside face of Parapet
Parapet
Roadway
Pitching
Cope
HIGH
WATER
Sea Wall
Facework
Backing
Hearting
Counterfort
Quay Wall
LOW
WATER

**Fig. 2.**

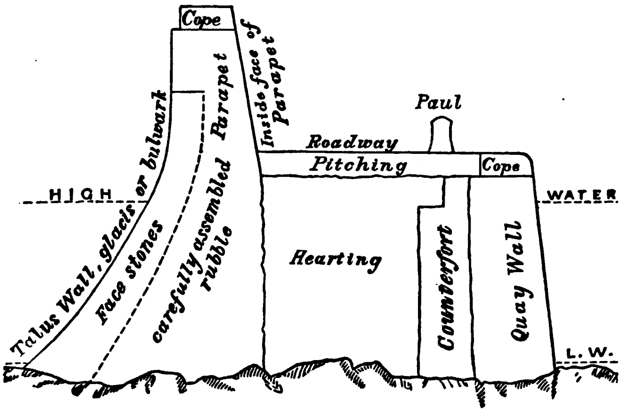

Cope
Inside face of Parapet
Parapet
Paul
Roadway
Pitching
Cope
HIGH
WATER
Talus Wall, glacis or bulwark
Face stones
carefully assembled rubble
Hearting
Counterfort
Quay Wall
L. W.

**Fig. 3.**

# CHAPTER II.

## GEOLOGICAL AND OTHER PHYSICAL FEATURES.

Apparent Signs of the existence of heavy Waves really due to gradual Attrition — Appearances leading to an Under-estimate of the Exposure — Ledges of Rock sometimes dangerous — Levels of Vegetation and of Surf-marks deceptive—Great Storms as contrasted with heavy Gales—Tempest of 1703—Cause of Storms—Level assumed by Mud a measure of Exposure—Action of Waves at bottom—Level of Mud in German Ocean—Waves on Dutch Coast.

THE engineer who is accustomed to contemplate the features of different sea-beaches is able to draw conclusions as to the exposure, the means of arriving at which cannot be imparted to another, but must be gained by personal experience alone. We shall therefore confine our remarks to one or two characteristics which admit of description. In some places these are obvious and easily judged of, but in others there are deceptive appearances which the engineer should be able to detect.

*Apparent Signs of the Effects of heavy Waves which are really due to gradual Attrition.*—Sir Henry de la Bêche mentions in his *Geological Manual*[1] that portions of the undercliffs at Pinhay, near Lyme Regis, have been destroyed, not so much by the action of the sea as by that of land-springs. The upper strata at that part of the coast are described as consisting of gravel, chalk, and greensand, resting on a bed of

[1] *Manual of Geology.* London, 1832.

clay, resulting from the disintegration of the greensand beds above, and of the upper part of the lias beds beneath. The strata which lie above the clay, being porous, admit of the percolation of the surface water, which descends till it reaches the impervious clay-bed, when it escapes by the easiest road to the sea. In escaping, it gradually washes away the outer parts of the clay-bed, thus depriving the upper strata of chalk and greensand of their support. The under bed of lias, which resists the action of the land-springs, forms a base which receives the ruins of the upper strata as they fall, until the sea in front, having gradually removed the bed of lias that supports them, allows them to drop upon the beach, where they are broken up by the sea. The waves therefore perform only a very minor part in the destruction of the cliffs; the principal cause being the gradual escape of water from the land-springs above.

At some parts of the coast of Scotland there are similar apparent proofs of the waves having exerted a great force; but the phenomena presenting these appearances, though no doubt indirectly due to the action of the sea, have not resulted from the stroke of any one wave, and form, therefore, no measure of its force. The coal formation which crops out along these shores consists of alternating beds of freestone and soft shale, in the latter of which, owing to its friable nature and open texture, the surf makes easy inroads by gradual attrition. The beds of sandstone, being of much harder texture, wear more slowly, and are therefore often seen projecting several feet beyond the subjacent shale. When the freestone beds have been sufficiently undermined, they break off *by their own weight,* and thus large tabular masses are detached, which, to a casual observer, present all the appearance of having been broken off by the impact of the waves, whereas the whole

effect is due to the geological accident of the alternation of strata possessing different degrees of hardness. The liability to unequal corroding action produced by breakers, when acting on rocks which are not of homogeneous texture and which vary in hardness, are not, however, confined to the sedimentary strata. Among the igneous rocks, Dr. Macculloch, in his *Western Islands of Scotland,* adduces the celebrated Fingal's Cave in Staffa, as an example of this inequality of degradation. Dr. Macculloch considers that the formation of the cave, which is 130 feet long, is due to the numerous joints in the basaltic columns which confront the sea at that spot, while the general character of the adjacent trap is a rock presenting fewer seams to the action of the waves.[1]

*Appearances leading to an Under-estimate of the Exposure.*—There are, however, in other districts deceptive appearances of a different kind, which may betray the observer into the opposite and more dangerous error of under-estimating the exposure, or mislead him as to the level reached by very high tides.

The engineer must remember, in drawing inferences from the rate of degradation, that this is not only dependent on the relative hardness of the rocks which are exposed to the waves, but also on the dip of the strata in relation to the direction of the breakers. Sir Henry de la Bêche says: "In many situations on the southern coasts of Devon and Cornwall, the slaty rocks dip in such a manner towards the sea that the waves have never effected more than the removal of some loose superficial matter, the same that covers all the hills in the vicinity. In fact a skilful engineer could not have protected

[1] *Description of the Western Islands of Scotland,* by John Macculloch, M.D., vol. ii. p. 11: Lond., 1819.

the coast better than has been accomplished by the dip of the strata."[1]

*Ledges of Rock dangerous.*—This remark of Sir Henry's suggests another source of danger which ought not to be overlooked. If a sloping direction of the strata has the effect of reducing the force against the coast by altering the direction of the surf, it is equally clear that where long ledges of rock cross the line of direction of a proposed pier, there may be expected an intensified action at the points of junction of the rock with the masonry. Long ledges of rock, though affording useful shelter where the works run parallel to them, are sources of danger where this parallelism cannot be preserved in laying out the lines of the piers. All attempts to carry works across those long narrow chasms which separate rocky shelves, or to cross creeks of considerable width, must be regarded as peculiarly hazardous, and special provisions are required for resisting the concentrated action which is common to these and all other places where the sea is *gorged.* It is therefore a fallacy to suppose that a chain of isolated outlying rocks necessarily furnishes facilities for the erection of a breakwater, as tending to reduce the cost of erection. On the contrary, although the existence of such rocks may reduce the amount of diving-bell work, it may increase to a great extent the risk of failure.

It must, however, be understood that cases occur where, in order to find sufficient harbour room, or to effect some particular object, it becomes necessary to erect sea-works in situations where the pent-up waves must be fully encountered. The sea-wall of the Victoria Harbour at Dunbar is an instance of this kind, for the basin that had to be enclosed forms the landward portion of a narrow creek. The outer wall has

[1] *Manual of Geology*, p. 71.

therefore not only to check, without any lateral relief, the *whole* of the waves, which formerly dashed into the creek, but owing to the outline of the coast it has also to encounter them nearly at right angles to their direction. The best form of harbour is, no doubt, to project two breakwaters or piers inclining towards each other seaward, so as to leave only a sufficient width as an entrance between them, for the waves will then slip easily towards the shore without striking heavily upon the masonry. I have known this easy form laid down as one of universal application; but when the same engineer had to show an alternative design of larger extent, he found himself compelled to cross the heavy incoming waves at right angles to their direction, so that the plan of universal application had no sooner been prescribed than it had in the same report to be abandoned for what would give more room, though at the expense of having to oppose his masonry to the full stroke of the waves.

*Levels of Vegetation and of Surf-marks deceptive.*—Mistakes as to the level of the highest tides are sometimes made by drawing too hasty conclusions from the presence of vegetable life. I have seen the thrift or "sea pink" (*Armeria maritima*), which seems to indicate unmistakably the limit of the rise of the highest tide, submerged, even in calm weather, during equinoctial springs. The tide of 8th January 1868 rose at Leith, according to Mr. George Robertson's observation,[1] four feet four inches higher than the calculated height for the day, and higher than any that had occurred for the previous eighteen years; and at Hull the same tide rose five feet five inches above the calculated height. Franklin mentions that a pond nine miles wide, and of an average depth of three feet, was acted on by a strong wind, which forced the

[1] *Proceedings, Royal Society of Edinburgh*, 1868, vol. vi. p. 296.

water from one side, so that it was laid bare, and the depth of water on the other side was increased to six feet.[1] Hence in defining any measurements which have the tide-level for a datum—as, for example, in clauses connected with river conservancy—it should always be stated that it refers to a given ordinary spring-tide uninfluenced by wind. Where there is no opportunity of making tidal observations, the level of the *lepas* or barnacle shell, which, where it is found, is generally very sharp and well defined, may be adopted as a help in fixing the mean level. The greatest height at which I have noticed this shell-fish varies from about half-way between the high-waters during neaps and ordinary springs, to about high-water of the highest neap-tides or of the lowest springs. Nor must the existence of grass and other land-vegetation be regarded as any decisive proof that the surf never reaches it. In the Shetland Islands there may often be seen large blocks of rock (and to these we shall afterwards refer), which, during storms, have been driven over the land at heights much greater than the level at which vegetation commences, and far above the ordinary run of the surf.

*Great Storms as contrasted with Heavy Gales.*—I should also add a caution applicable specially to all inquiries regarding the occurrence of storms. It is a common and dangerous mistake to trust to the highest marks of the surf that may be visible on the beach, and which are probably the vestiges of gales that have occurred within the previous year or two. Any such experience as this is greatly too limited. There is a vast difference between a "*heavy gale*" and a "*great storm*," such, for example, as that of January 1839, when the wind reached a force which, in this country, has since been only once exceeded,

[1] *Report of the Commission of Agriculture for the Year* 1870, p. 610. Washington, 1871.

viz. in January 1868. And these storms, great as they were, must be regarded as only heavy gales, when we contrast their effects with those of the celebrated hurricane which visited the South of England on 26th November 1703, and which scattered ruin, desolation, and death on every side. Among the records of its effects I have selected the following facts (from the historical narrative published in 1769,[1] and Dr. Derham's paper in the London *Transactions*); and although these extracts may satisfy us that no subsequent storm has equalled this one, they still prove the dreadful violence with which marine works *may possibly* be assailed.

The loss of men and ships in the Royal Navy was 12 vessels, 1611 men, and 524 guns.

Besides these we find the following items:—

| | |
|---|---|
| Vessels lost at sea | 160 |
| Persons drowned in the Thames | 24 |
| Wherries lost in the Thames | 500 |
| Persons killed in London | 123 |
| Total number lost at sea | 8000 |
| Houses blown down | 800 |
| Churches stripped of lead | 100 |
| Steeples blown down | 7 |
| Windmills destroyed | 400 |
| Trees blown down | 29,000 |
| Stacks of chimneys blown down in London | 2000 |

So violent a tempest as this may well be regarded as almost preternatural, and an engineer could hardly be blamed although his work had been unable to withstand its assault. Still, we must ever be cautious in giving too much weight to the effects of heavy gales which have but recently occurred, and to which the name of "*storm*" is too often improperly given.

[1] *An Historical Narrative of the great and tremendous Storm which happened Nov.* 26, 1703. London, 1769.

The real cause of great storms is, as described in my paper,[1] what I termed the steepness of the *barometric gradient,* or the relation subsisting between the difference at any one time between two barometers, combined with the distance between them; and it is by the barometric gradient that the expected force of the wind is now predicted for all weather forecasts.

Storms occur indeed but seldom, perhaps not once in ten or twenty years, and very *great* storms are, as we have seen, of still rarer occurrence, whereas hardly a winter passes in which one or two heavy gales do not take place. The error of confounding the very different indications of gales with the effects due to storms, may be well illustrated by the analogous error in bridge engineering of assuming as our data the levels of ordinary freshes instead of those of great floods, which, when they do occur, occasion, as every one knows, vastly greater damage.

*Level assumed by Mud a measure of the Exposure.*—I have elsewhere[2] referred to a feature which will be found of very considerable value in judging of the exposure of a coast. This is *the level below the surface of low-water at which mud reposes* on the bottom of the sea. It may appear unlikely that the disturbance of the surface of the sea occasioned by storms should be propagated to great depths, but there is no want of evidence on this head. Mr. Airy, the Astronomer Royal, has shown, on theoretical grounds,[3] that, at a depth equal to the length of the wave, the motion is $\frac{1}{535}$ of that at the surface, and mentions that heavy ground-swells break in a depth of one hundred fathoms. Sir J. Coode found, from underwater examinations made with the diving dress, that

[1] Read at the meeting of the *Scottish Met. Soc.* 26th June 1867.

[2] *Proceedings Royal Soc. Edin.* vol. iv. p. 200.

[3] *Encyclopædia Metropolitana,* article "Waves."

the shingle of the Chesil Bank was moved during heavy winter storms at a depth of eight fathoms, and Captain E. K. Calver, R.N.,[1] has seen waves six or eight feet high change their colour from the abrasion of the bottom after passing into water of seven or eight fathoms. The late Mr. Robert Stevenson, in his paper on the alveus or bed of the German Ocean,[2] says—"The dispersion of fishes, evinced by their disappearance from the fishing grounds in stormy weather, tends to show the disturbance of the ocean at the depth of thirty or forty fathoms. This observation I have frequently had an opportunity of making near the entrance of the Firth of Forth. Numerous proofs of the sea being disturbed to a considerable depth have also occurred since the erection of the Bell Rock Lighthouse, situate upon a sunken rock in the sea twelve miles from Arbroath in Forfarshire. Some drift stones of large dimensions, measuring upwards of thirty cubic feet, or more than two tons weight, have, during storms, been thrown upon the rock from deep water. These large boulder stones are so familiar to the lighthouse keepers at this station as to be by them termed 'travellers.'"

To these may be added a curious example of the action of the waves on the bottom near Burlington Harbour, where a well was sunk which discharged water whenever the tide rose to within four feet two inches of the level of its mouth, and, 'during storms," says Dr. Storer, who gave an account of it in 1815, "the water flows in waves similar[3] to the waves of the sea." These phenomena were attributed to the pressure of the tide and waves on an outlet of the spring, which was on good grounds supposed to exist in the bottom of the bay outside.

[1] *The Wave Screen*, by E. K. Calver, R.N. London, 1858.
[2] *Wernerian Nat. Hist. Soc. Trans.* 1820. [3] *Phil. Trans.*, 1815.

From these statements it may easily be inferred that *in exposed situations mud cannot repose near the surface.* No one would expect to find a muddy shore confronting an open sea, where the deep water approached closely to the shore, though he would not express surprise at finding such a beach on the borders of a land-locked bay or of a sheltered estuary. Although the *absence* of mud in any locality proves nothing, because the tide-currents may sweep it away, or the geological formation may not produce it, yet its *presence* seems both a delicate and certain test of the lowest limit to which the disturbance originating at the surface has reached. At Allippey, in India, there is a peculiar oily mud, existing in such enormous quantities that, when disturbed by the monsoons, the *sea itself* becomes a mass of fluid greasy mud, which destroys the waves. See Mr. G. Robertson's description (*Roy. Soc. Edin. Proceedings*), who quotes a letter from Mr. Crawford of Allippey to the effect that the mud is an irruption from the bottom, which takes place only during the monsoons, and adds—"About five years ago, for about four miles down the coast, and from the beach out to sea for a mile and a half, the sea was nothing but liquid mud; the fish died, and as these cones (of mud) reared their heads above the surrounding mud they would occasionally turn over a dead porpoise and numerous fish. The boatmen had considerable difficulty in urging their canoes through this to get outside of it. The beach and anchorage roads presented then a singular appearance—nothing to be seen but those miniature volcanoes, some silent, others active—perfect stillness all around the ships in the roads as if in some dock, with a heavy sea breaking in seven fathoms outside." This enormous amount of mud, due to volcanic agency, is, however, altogether abnormal, and unknown in any other part of the

world. It does not therefore affect in any way the mud test to which I have referred, and which I shall now further illustrate by reference to different parts of the coasts of Britain.

*German Ocean.*—Applying this test to the German Ocean, we find no mud in the immediate neighbourhood of Whalsey, in Zetland, and, as I have already said, no conclusion can be drawn from its absence; but within twenty-five miles we find it in from eighty to ninety fathoms below low water. In the latitude of Wick it occurs in from sixty to seventy fathoms; in the latitude of Kinnaird Head we have it, on the Norwegian side, in forty to fifty fathoms; in the Moray Firth, abreast of Banffshire, we find it in depths of about thirty-five fathoms; while, as we proceed towards the more sheltered parts of that firth, we find it rise to within twenty fathoms of low-water, and within the Dornoch Firth we find it within sixteen, and close in, under the shelter of the Sutherland shore, we find it in only eight fathoms under the low-water surface. In the latitude of the Firth of Forth it appears in depths of from thirty to forty fathoms; and proceeding up that Firth we have a good illustration of the truth of this mud test; for, on looking at Fig. 4, which represents the relative level of the muddy bottom on the southern shore, we find it gradually rising nearer to the low-water level, in proportion as the shelter increases, from twenty-two fathoms at Dunbar up to three fathoms off Leith; and were the section carried beyond Queensferry, we should find the mud actually emerging above the surface at low-water, even although the current gets stronger as we ascend the narrow estuary. Fig. 5 represents a similar section of the northern shore of the Firth of Forth, and here the mud gradually rises from twenty-two fathoms off Fifeness up to *eight* fathoms at

Burntisland; whereas near Leith, on the shore opposite (*vide* Fig. 4), it exists, as we have said, in *three* fathoms, which accords well with the known fact that the heaviest sea passes on the north side of the Island of Inchkeith, and not on the south.

Leaving this small firth or inlet, which was only adverted to as a proof of the applicability of the test to facts generally recognised, we return to the German Ocean, and observe that towards its southern portion mud is found within about


Fig. 4.

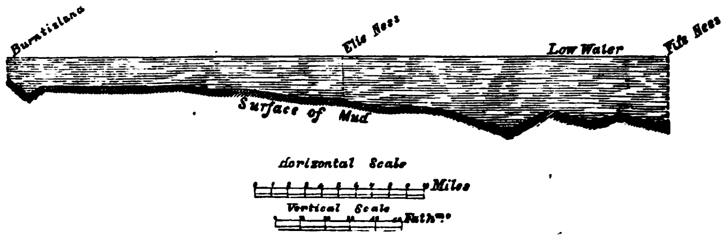



Fig. 5.

twenty fathoms of the surface, and under lee of the Dogger-bank within fifteen fathoms; and, proceeding still farther south, we find it on the coast of Holland at depths of from twelve to sixteen fathoms, and at only eight fathoms at the mouth of the Elbe.

*Waves on Dutch Coast.*—Now, the violence of the waves upon the shores of the German Ocean certainly decreases in much the same proportion as the rise in the level of the mud, there being a gradual decrease as we come from Shetland and the North of Scotland—where, as will be afterwards shown,

wonderful energy is displayed by the sea—to the coasts of Holland, where the waves are much modified. Although it is no doubt true that the flat-bottomed vessels of the Dutch are built purposely for resisting a heavy surf, still the fact of their being able to take the open beach in nearly all weathers along that coast without any protection from harbours, goes far to prove that the waves are much reduced before they reach the Dutch coast. The late Mr. R. Stevenson remarks:[1]—"On this great range of coast, from Scheveling to the Helder, there is a succession of fishing towns without a single harbour capable of receiving a vessel of almost any description. When the Dutch fisherman therefore arrives upon this coast with a cargo, he allows his vessel to take the ground, when she surges or is driven before the breakers to high-water mark upon the beach." The comparatively sheltered state of these southern shores is further corroborated by the practice of the inhabitants in designing the sea walls which protect their coast. Mr. Hyde Clark says:[2]—"On the coast of Zealand they (the Dutch) reckoned 8½ feet as the greatest height to which any wave would be *thrown*." In short, although in the German Ocean we shall find in any parallel of latitude almost every gradation of depth between the low-water margin of the shores where there is no depth at all, and the maximum sounding in the sea outside, yet *mud nowhere appears to exist in shoal water in any place where there is a heavy sea.*

The same general result may be found on the west coast of the British Isles. While on the west of Ireland mud does not lie nearer the low-water level than from forty to sixty fathoms, patches may be found on its eastern or more sheltered side, to the north of Dublin, at only twenty fathoms; and half-way up

[1] "Journal of a Trip to Holland," *Scots Magazine*, 1817.

[2] *Min. Civ. Eng.*

Belfast Lough, where there is good shelter, it may be found at five fathoms below the surface.

*If, therefore, we find in front of a proposed harbour that mud reposes within a few fathoms of the surface, I believe we have in that fact certain ground for concluding that marine works will never be assailed by a very heavy sea.*

# CHAPTER III.

## GENERATION OF WAVES.

Line of Maximum Exposure—Law of the Ratio of the Square Roots of Distances from the Windward Shore—Coefficient for Heavy Gales—Formulæ for Long and Short Distances—Maximum recorded Heights of Waves in Large Bodies of Water—Partial Action of the Wind—Linear Extent of Gales—Line of Maximum Effective Exposure—Oblique Action of Waves.

EFFECTS OF GEOGRAPHICAL CONFIGURATION OF COAST.

Tortuous Channels—Expanding Channels—Propagation of Ground-Swell—Direction of the Coast Line in relation to the Line of Exposure—Length and Velocity of Waves.

*Line of Maximum Exposure.*—In comparing an existing harbour with a proposed one, perhaps the most obvious element is what may be termed the *line of maximum exposure,* or, in other words, the line of greatest *fetch* or *reach* of open sea, which can be easily measured from a chart. But though possessed of this information, the engineer still does not know in what ratio the height of the waves increases in relation to any given increase in the line of exposure.

*Law of the Ratio of the Square Roots of the Distances from the Windward Shore.*—In 1850 I instituted a series of observations on the Union Canal, on a small fresh-water loch, and also on the Firth of Forth and the Moray Firth, with the view of determining the law of this increase; and in the *Edin. Phil. Journal* for 1852 I stated the height of the waves to be most nearly in "*the ratio of the square root of their distances from the wind-*

*ward shore,*" or when $h$ = height of wave, $d$ = distance, and $a$ is a coefficient, varying with the strength of the wind:

$$h = a\sqrt{d}.$$

The truth of this law I have since then had various opportunities of testing.[1] The accompanying table contains

| 1<br>PLACE OF OBSERVATION. | 2<br>Length of Fetch in Miles Nautical. | 3<br>Observed Height of Wave. | 4<br>Height due to Fetch, calculated from Formula, $h = 1.5\sqrt{d}$. | 5<br>Height due to Fetch, calculated from Formula, $h = 1.5\sqrt{d} + (2.5 - \sqrt[4]{d})$ *Vide* p. 29. |
|---|---|---|---|---|
| Scapa Flow . . . | 1.0 | 4.0 | 1.5 | 3.0 |
| Firth of Forth . . | 1.3 | 1.8 | 1.8 | 3.2 |
| Granton . . . | 2.8 | 4.0 | 2.5 | 3.75 |
| Craignure . . . | 3.5 | 2.0 | 2.9 | 3.9 |
| Granton . . . | 6.0 | 4.0 | 3.7 | 4.6 |
| Lough Foyle . . | 7.5 | 4.0 | 4.1 | 4.96 |
| Clyde . . . . | 9.0 | 4.0 | 4.5 | 5.25 |
| Colonsay . . . | 9.0 | 5.0 | 4.5 | 5.25 |
| Dysart . . . | 10.0 | 4.2 | 4.9 | 5.5 |
| Invergordon . . | 11.0 | 3.5 | 5.0 | 5.7 |
| Lough Foyle . . | 11.0 | 5.0 | 5.0 | 5.7 |
| Glenluce Bay . . | 13.5 | 5.5 | 5.6 | 6.1 |
| Anstruther . . . | 24.0 | 6.5 | 7.5 | 7.7 |
| Lake of Geneva, stated by Minard[2] . . | 30.0 | 8.2 | 8.2 | 8.37 |
| Buckie . . . | 31.0 | 7.0 | 8.4 | 8.5 |
| ,, | 38.0 | 7.0 | 9.2 | 9.2 |
| ,, | 38.0 | 8.0 | 9.2 | 9.2 |
| ,, | 40.0 | 8.0 | 9.55 | 9.5 |
| Macduff . . . | 44.5 | 8.0 | 10.02 | 9.9 |
| ,, | 45.5 | 10.0 | 10.20 | 10.0 |
| Douglas, Isle of Man, St. George's Channel | 65.10 | 10.12 | 12.0 | ...... |
| Kingstown[3] . . . | 114.0 | 15.0 | 16.0 | 15.25 |
| Sunderland, distance measured from Broken Bank . . . | 165.0 | 15.0 | 19.3 | 18.15 |
| | | 149.82 | 165.57 | 162.68 |
| | Mean . | 6.3 | 6.97 | 7.39 |

[1] It follows from this law that the height of embankments of reservoirs above the water-surface should, *cœteris paribus*, be proportional to the *square roots* of the lengths of water over which the wind acts.

[2] *Cours de Construction des Ouvrages Hydrauliques.* Liege, 1852, p. 8.

[3] Some of the extreme waves appeared to be about twice this height, but it is of course very difficult to judge the height of such "*toppling*" waves by the eye.

some of the observations made in 1850-52, as well as later observations on the effects of heavy gales, which could only be made at long intervals of time. Some of these were made for me in various quarters by resident engineers and inspectors of different marine works. For one observation in the Irish Sea I am indebted to the late Mr. R. Mallet, C.E., and for many others to the late Mr. Middlemiss, Inspector of Harbour Works. Several are from my own observations, and two of the heights are from estimation by the eye.

*Coefficient for Heavy Gales.*—Some of these results[1] have also been laid down in Fig. 6, so as to form a *storm-curve.* Within the limits of the observations the following very

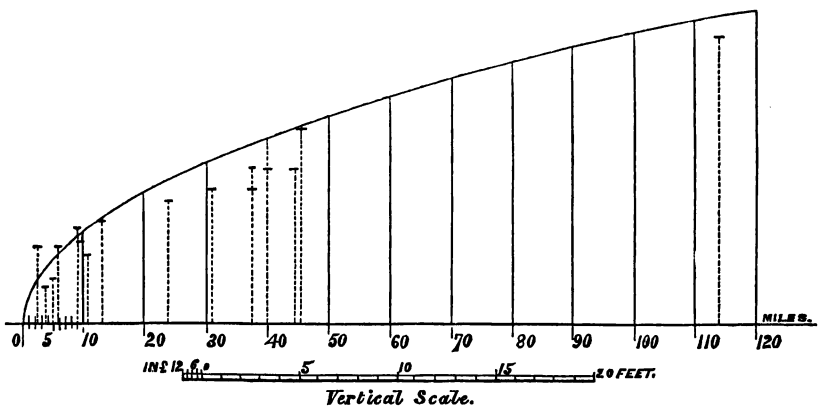



Fig. 6.

simple and easily remembered expression, which is represented by the parabolic curve in the diagram, will indicate pretty nearly the height of waves during heavy gales, at least in seas which *do not greatly differ in depth* from those where the

[1] The later observations are not given in the woodcut, which was made several years ago.

stations were situated. If $h$ = the height of the wave in *feet* during a strong gale, $d$ = length of exposure in *miles;* then, unless the water is of insufficient depth to allow the waves to be fully formed, or becomes so shallow as to reduce their height after they are formed—

$$h = 1.5 \sqrt{d}.$$

The heights calculated according to this formula are given in column 4 of the foregoing Table, and the observed heights in column 3.

*Formula for Short Distances.*—For most practical purposes of the engineer this formula will be found sufficiently accurate. In order, however, to secure strictly comparable results, an anemometer would be required. But it must be observed that in short fetches in narrow lochs or arms of the sea, waves are raised higher during very violent gales than the formula indicates; though such waves do not go on progressing in height in the same high ratio for any considerable distance. With the view of rendering the formula more exact for short reaches and violent squalls, the following will be found more suitable:—

$$H = 1.5 \sqrt{D} + (2.5 - \sqrt[4]{D}).$$

As already mentioned, however, the first easily remembered formula will be found quite sufficient for all ordinary gales and distances, and for bodies of water similar to those where the observations were made. Column 5 of the Table of Observations contains the results given by this last formula.

Mr. Hawkesley, in *Min. Civ. Eng.*,[1] published in 1861, says—" In the heaviest gales with which the British Coast was visited, their (the waves) height in yards was represented by the square root of the length in yards of the run of any

[1] Vol. xx. p. 361.

one wave divided by forty." This testimony is satisfactory as corroborating the law of increase of the square root of the distance, which was given in my formula of 1852, but assigns a coefficient which gives much higher results than my experience warrants. The following Table may be found convenient as a general guide in estimating the heights due to different fetches :—

TABLE showing APPROXIMATE HEIGHTS of WAVES due to Lengths of Fetch.

| Miles. | Heights. | Miles. | Heights. | Miles. | Heights. | Miles. | Heights. |
|---|---|---|---|---|---|---|---|
| 1 = | 3.0 | 20 = | 7.1 | 39 = | 9.4 | 130 = | 17.1 |
| 2 | 3.4 | 21 | 7.2 | 40 | 9.5 | 140 | 17.7 |
| 3 | 3.8 | 22 | 7.4 | 41 | 9.6 | 150 | 18.4 |
| 4 | 4.1 | 23 | 7.5 | 42 | 9.7 | 160 | 19.0 |
| 5 | 4.3 | 24 | 7.6 | 43 | 9.8 | 170 | 19.5 |
| 6 | 4.6 | 25 | 7.8 | 44 | 9.9 | 180 | 20.1 |
| 7 | 4.8 | 26 | 7.9 | 45 | 10.0 | 190 | 20.7 |
| 8 | 5.0 | 27 | 8.0 | 46 | 10.2 | 200 | 21.2 |
| 9 | 5.3 | 28 | 8.1 | 47 | 10.3 | 210 | 21.7 |
| 10 | 5.6 | 29 | 8.3 | 48 | 10.3 | 220 | 22.2 |
| 11 | 5.7 | 30 | 8.4 | 49 | 10.5 | 230 | 22.7 |
| 12 | 5.9 | 31 | 8.5 | 50 | 10.6 | 240 | 23.2 |
| 13 | 6.0 | 32 | 8.6 | 60 | 11.6 | 250 | 23.7 |
| 14 | 6.2 | 33 | 8.8 | 70 | 12.5 | 260 | 24.2 |
| 15 | 6.3 | 34 | 8.8 | 80 | 13.4 | 270 | 24.6 |
| 16 | 6.5 | 35 | 8.9 | 90 | 14.2 | 280 | 25.1 |
| 17 | 6.7 | 36 | 9.0 | 100 | 15.0 | 290 | 25.5 |
| 18 | 6.8 | 37 | 9.2 | 110 | 15.7 | 300 | 26.0 |
| 19 | 7.0 | 38 | 9.3 | 120 | 16.4 | | |

*Maximum recorded Height of Waves in Large Bodies of Water.*—The only observations which I have met with for longer fetches than those in the Table are a height of 14 feet 10 inches, as ascertained by the Comte de Marsilli, in 1725,[1] in the Mediterranean, where the longest possible fetch is

[1] *Histoire Phisique de la Mer*, par Louis Ferdinand, Comte de Marsilli. Amsterdam, 1725.

about 600 miles. At the harbour of Lybster, Caithness-shire, with the same maximum length of fetch, where observations were made for me during a period of several years, the waves at the shore attained the height of 13½ feet. At Sunderland I found the waves to be also about 13 feet high at the pier-head; but the height, as in the two former cases, was no doubt reduced by the shallow water near the shore. At Wick, with much the same exposure, waves of about 40 feet have been observed to strike the breakwater. Commander Dayman observed that the highest waves off the Cape of Good Hope were 20 feet,[1] and Mr. Cockburn Curtis informs us that the gales which produce these rollers extend to from 300 to 600 miles. In the Atlantic Ocean, Dr. Scoresby, when at sea, measured the waves with great care and accuracy on different occasions. He says[2]—"In the afternoon of this day (4th March 1848) I stood sometimes on the saloon deck or cuddy roof watching the sublime spectacle presented by the turbulent waters. I am not aware that I ever saw the sea more terribly magnificent." Dr. Scoresby then ventured to the port paddle-box. "Here also," says he, "I found at least *one half* of the waves which overtook and passed the ship were far above the level of my eye" (30 feet 3 inches above the level of the sea). "Frequently I observed long *ranges* (not acuminated peaks) extending 100 yards perhaps on one or both sides of the ship, the sea then coming nearly right aft, which rose so high above the visible horizon as to form an angle estimated at 2 or 3 degrees (say 2½°) when the distance of the wave-summit was about 100 yards from the observer. This would add nearly 13 feet to the level of the eye, and this measure of elevation was by no means uncommon, occurring, I should think, at least once in half-a-dozen

[1] *Min. Civ. Eng.* [2] *Brit. Assoc. Rep.* 1850.

waves. Sometimes peaks of crossing or crests of *breaking* seas would shoot upwards at least 10 or 15 feet higher. The *average wave* was, I believe, fully equal to that of my sight on the paddle-box, or more—that is $\frac{30}{2} = 15$ feet or upward, and the *mean highest waves*, not including the broken or acuminated crests, about 43 *feet above the level of the hollow occupied at the moment by the ship*." [1]

*Partial Action of the Wind.*—Dr. Scoresby adds that "in respect to form we have perpetual modifications and varieties, from the circumstance of the inequality of operation of the *power* by which the waves are raised. Were the wind perfectly uniform in direction and force, and of sufficient continuance, we might have in wide and deep seas waves of perfectly regular formation. But no such equality in the wind exists. It is perpetually changing its direction within certain limits, and its force too, both in the same place and in proximate quarters. Innumerable disturbing influences are therefore in operation, generating the varieties observable in natural seas."

Any one who has watched attentively the forms of waves will confirm this statement. During the continuance of a gale they assume a very irregular appearance, and defy all attempts to trace any individual undulation for a long distance. This irregularity in the action of the wind may be still better seen in a field of ripe corn. At some parts of the moving stalks there appears a concentration to a very near centre, while all around there is but little deflection. In short, while the whole field appears to be acted on by the wind, numerous small patches of greater depression are here and there to be seen, and these depressions quickly disappear, while others are as speedily formed at some distance in

[1] *Brit. Assoc. Rep.* 1850, p. 26.

advance. Proofs of the same irregularity of action may be found after the gale has subsided, providing it has been strong enough to lay the corn. Instead of finding the whole of the surface depressed, the stalks will be found in some places erect, and at others flattened, and these spots alternate the one with the other, without any regard to regularity.

*Linear Extent of Gales.*—The reader must not, however, assume that the height will in every case be proportional to the line of exposure. Though this be true of the smaller class of seas it cannot be extended to large oceans. It is probable that few gales are of sufficient extent to act over such a distance as between Europe and America; and though it did, we may certainly conclude that there is a limit to the height to which the waves can be raised. Those noticed by Scoresby in the Atlantic, which were 43 feet, may perhaps have nearly attained the maximum height for any gale, however great the depth, or however long the distance over which it acts. Though it is generally believed that the Atlantic gales have a rotatory motion, it is still quite consistent with that theory that the undulations should continue to be raised in one direction by the action of the storm for very considerable distances. The late Colonel Reid, in his *Development of the Law of Storms*, says, at p. 32—"I apprehend that the great undulations raised by the wind in revolving storms are raised along the radii of the whirlwind circle, and roll straight onwards in the direction of tangents to the circle of the whirlwind." Again, at p. 35—"The undulations raised by storms sometimes roll on to a very great distance. . . . I was in Bermuda when the hurricane of 1839 occurred, and distinctly heard the sea breaking loudly against the south shores on the morning of the 9th September, full three days before the storm reached the islands, as recorded in the tables

of the state of the weather, kept at the central signal-station. At that time the hurricane was still within the tropics, and distant ten degrees of latitude. *As the storm approached, the swell increased, breaking against the southern shores with louder roar and great grandeur,* until the evening of the 12th September, when the whirlwind storm, reaching the Bermudas, set in there." From these facts Colonel Reid draws the following conclusion:—"I think it probable that the heaviest swell proceeding from a storm may be that which is propelled forward in the track which the storm is itself following, as the undulations in this case would be constantly receiving renewed impulses from the storm in its progression. This may account for the unusual degree of grandeur with which the undulations broke against the southern shores of the Bermuda Islands just before the storm set in."

Mr. Redfield[1] says that on one flank of the Atlantic storms the direction of the wind coincides with that of the wave propagation, and he also gives the extent of the following remarkable hurricanes, which I have arranged in a tabular form:—

| Storm of | Followed a Straight Course for | Mean Velocity. |
|---|---|---|
| 23d June 1831 | 1700 miles. | 17 miles per hour. |
| 29th Sept. 1830 | 1800 " | 25 " " |
| 10th Aug. 1831 | 2000 " | 13½ " " |
| Sept. 1804 | 2200 " | 15½ " " |
| 12th Aug. 1835 | 2200 " | 15½ " " |
| Aug. 1830 | 3000 " | 17 " " |
| 17th Aug. 1827 | 3000 " | 11 " " |

To these instances we may add that the westerly gale of December 1862 blew for two and a half days at Edinburgh

[1] *Journal Franklin Institute*, vol. xix. 1837.

without almost any variation in direction. It will be found, by any one paying attention to the subject, that gales of as long continuance in one direction as that referred to, which was not specially selected for illustration, are by no means of rare occurrence in Britain.

*Line of Maximum Effective Exposure, Oblique Action of Waves.*—It does not follow, however, that the line of maximum exposure is in every case the line of maximum *effective* force of the waves, for this must depend not only on the length of *fetch,* but also on the angle of incidence of the waves on the walls of the harbour. What may be termed the line of *maximum effective exposure* is that which, after being corrected for obliquity of impact, produces the maxi mum result, and this can only be ascertained from the chart by successive trials. Let $x =$ the greatest force that can assail the pier, $h =$ height of waves which produce (after being corrected for obliquity) the maximum effect, and which are due to the line of maximum effective exposure, sin $a =$ sine of azimuthal angle formed between the directions of pier and the line of maximum effective exposure. Then, when the force is resolved normal to the line of the pier—

$$x \propto h \sin^2\alpha\,;$$

but if the force be again resolved in the direction of the waves themselves, the expression becomes

$$x \propto h \sin^3\alpha.$$

It should not, however, be forgotten, in connection with this subject, that in some cases there are qualifying elements to which special attention requires to be given. The waves, for example, when approaching the land obliquely, often alter their direction when they get close to the shore, in consequence of a change in the depth, and from this cause they strike more nearly at right angles to the general line of the

beach, and thus strike with greater force than the line of maximum effective exposure would lead us to expect.

*Reduction of Force due to Oblique Action.*—Although experimental observations are still wanted, we are not without practical proof of the reduction of the force of waves where the obstacle lies obliquely to their direction. At the harbour-works of Lybster, in 1851, during the erection of the pier-head, which stands at right angles to the waves, occasional damage took place, and during one gale three stones about a ton each were thrown down, while the wharf wall immediately adjoining, which was parallel to the motion of the waves, was never injured in the slightest degree, although it was of far inferior strength. From the repeated injuries that the pier-head sustained while it was in progress, it was found necessary to connect together the whole of the stones with bolts—a precaution which was not required at the quay wall. The late Mr. James Bremner of Wick, who had much experience in sea works, recommended that piers should be laid out so as to form a horizontal angle of not more than 25° with the heaviest billows; while it is right to state, on the other hand, that Professor Airy considers that it is safer for the sea to impinge at right angles.

The extraordinary difference between waves acting at right angles, and others having even a very slight amount of obliquity, has been shown in the most unmistakable manner in the Wick Breakwater, elsewhere referred to, where all attempts to make the work stand, when exactly at right angles to the sea, have hitherto been unsuccessful. Although I know no other work which is exposed to the same class of waves, still the lesson may be useful in other less exposed situations, by directing the attention of the engineer to the necessity of adopting additional precautions.

The waves, on entering the bay of Wick, assume a curved form *in plano*, and impinge upon the outer part of the outer kant of the breakwater at nearly normal incidence. It was found by observation, that while waves coming from the direction of S. by E. struck the outer part at normal incidence, they struck the landward end of the same kant at an angle of incidence of 81°, giving 9° of obliquity. Other south-easterly seas, which struck the outer part of the outer kant at an angle of incidence of 73° struck the landward part of the same kant at an angle of incidence of 68°, giving 5° of greater obliquity. Even these small deviations from normal incidence have thus been proved most materially to decrease the intensity of the impact.

## EFFECTS OF GEOGRAPHICAL CONFIGURATION OF THE COAST.

*Narrow Tortuous Channels and Expanding Channels.*—The value of the line of maximum effective exposure varies in certain localities with the geographical configuration of the land. The harbour of Inverary lies at the termination of Loch Fyne, which, from its being narrow and somewhat tortuous, might lead to the expectation that no heavy waves would reach its upper end. I have been informed, however, that waves of very considerable height strike the pier of Inverary, and are occasionally found troublesome to the small steamer which crosses the St. Catherine's Ferry. From the mountainous character of the country, it is probable that when a strong gale blows, it successively alters its direction with that of the valleys, so as in a great measure to counteract the effects of the *winding* of the loch.

At Craignure, in Mull, on the other hand, where the channel enlarges, the height of the waves is decreased. Craignure Bay, on the northern shore of the Island of Mull,

lies at the eastern end of the Sound of Mull, and has a line of maximum exposure extending for about 25 miles up Loch Lynnhe. As the water is deep, this circumstance would lead us, though the channel is no doubt narrow, to expect from the formula that waves approaching eight feet in height would break upon the shore at Craignure, but I doubt whether they ever attain nearly such a magnitude. The tides may perhaps have some effect in reducing their height; but if we consider the geographical configuration, we shall find that there are other causes to account for the reduction of height. At the southern termination of Loch Lynnhe, where Craignure lies, the channel is bifurcated, one branch leading southwards between the Islands of Lismore and Mull, and the other leading northwards through the Sound of Mull. When, therefore, waves which are generated in the long fetch of Loch Lynnhe reach the southern end of Lismore Island they lose their height by expanding to the south round Lismore, to the north into the Sound of Mull, and to the west into Craignure Bay. It will be seen from the subjoined register how small a height the waves attained during the time specified, which extends from September till February of the years 1853-54.

HEIGHT of WAVES at CRAIGNURE, when wind blew down LOCH LYNNHE.

| 1853. | | Ft. | in. | 1863. | | Ft. | in. |
|---|---|---|---|---|---|---|---|
| Sept. 25. | Gale . . . . | 2 | 3 | Dec. 28. | Moderate . . | 0 | 9 |
| Oct. 6. | Very strong . | 2 | 2 | ,, 30. | Fresh gale . . | 2 | 0 |
| ,, 11. | Moderate . . | 1 | 0 | ,, 31. | Do. . . | 1 | 5 |
| ,, 12. | Light . . . | 0 | 9 | 1854. | | | |
| Dec. 6. | Light . . . | 0 | 5 | Jan. 4. | Fresh . . . | 1 | 0 |
| ,, 13. | Strong . . . | 1 | 4 | ,, 5. | Strong . . . | 1 | 9 |
| ,, 14. | Fresh . . . | 1 | 4 | ,, 6. | Moderate . . | 1 | 0 |
| ,, 15. | Moderate . . | 0 | 8 | ,, 8. | Strong . . . | 2 | 4 |
| ,, 20. | Light . . . | 1 | 1 | ,, 9. | Moderate . . | 1 | 4 |
| ,, 26. | Fresh . . . | 0 | 10 | ,, 10. | Moderate . . | 0 | 10 |
| ,, 27. | Moderate . . | 0 | 6 | | | | |

*Propagation of Ground-swell in Narrow Channels.*—At Dunoon, in the Firth of Clyde, the ground-swell, after coming through the narrow passage at the Cumbraes, is still from 7 to 9 feet high. It therefore passes through a neck of only $1\frac{1}{4}$ mile broad, and is propagated through a channel $1\frac{3}{4}$ mile broad for a distance of 14 miles *when there is no wind;* it even reaches Gourock and Greenock after turning through more than a right angle, and after losing height by divergence into several capacious lochs. The ground-swell at the Firth of Forth passes in the form of heavy waves above Queensferry, which is about $\frac{8}{10}$ of a mile broad, and is upwards of 30 miles from the mouth of the Firth.

*Direction of the general Coast Line in relation to the Line of Exposure.*—In 1857 I issued a series of queries among fishermen and others at various parts of the coast of Scotland, as to the direction from which the heaviest seas come upon the coast. Though there are some apparent anomalies, the general result derived from the statements of nearly 300 fishermen and others is, that at the distance of $1\frac{1}{2}$ mile seaward of the coast line, the heaviest waves come in the direction of the longest fetch, which goes to corroborate the supposition that gales frequently act over large extents of water. On the shore, however, the force is much modified by the angle formed by the coast with the line of maximum exposure. On the east coast it was found that, at about $1\frac{1}{2}$ mile off the shore, the north-east is generally the worst direction; but for that part of the coast which extends from the Tay to Aberdeen, the south-east waves generally break heaviest upon the shore. This arises from the small angle which the north-east bearing makes with the land at this part of the coast. *The most exposed coasts may therefore be regarded,* cæteris paribus, *as those on which the waves gene-*

*rated in the line of maximum exposure come dead-on upon the shore.*

*Length and Velocity of Waves.*—The longest distance apart, from crest to crest, of the Atlantic waves, observed by Scoresby, was 790 feet.[1] His other results are as under:—

Altitude, 43 feet.
Mean distance between waves, 559 feet.
Interval of time between each wave, 16 seconds.
Velocity of each wave per hour, 32½ miles.

The ships of the United States Navy have lately been engaged making observations of the dimensions and speed of deep-sea waves, and the following are some of the results already obtained:—The longest recorded waves measured half a mile from crest to crest, with a period of 23 seconds. Waves having a length of 500 or 600 feet, and periods of 10 to 11 seconds, are the ordinary storm waves of the North Atlantic. In regard to the heights of waves, the most trustworthy measurements show from 44 to 48 feet to be a remarkable height. Waves having a greater height than 30 feet are not commonly encountered.

The following were observed by Sir James N. Douglass at the Bishop Rock, on whose authority they are stated:—

| | | | |
|---|---|---|---|
| 8 ft. waves, | 35 in a mile, | 171 ft. apart— | 8 per min. |
| 15 " " | 5 and 6 " " | 1200 and 1000 " " — | 5 " |
| 20 " " | 3 " " | 2000 " " — | 4 " |

The late Mr. Mackintosh, lightkeeper at the Calf of Man, in the Irish Sea, informed me that he had, on three different occasions, counted 13½ waves between the Calf of Man and the Chickens Rock. This distance gives about 490 feet as the length of the waves in this comparatively landlocked branch of the ocean.

[1] *Life of William Scoresby*, by Dr. Scoresby Jackson. London, 1861, pp. 159 and 324.

## CHAPTER IV.

### FORCE OF THE WAVES.

Force in small bodies of Water—Remarkable destructive Effects at Whalsey Skerries in Shetland—Extraordinary force of Sea at Wick Breakwater—Marine Dynamometer—Formula—Other forms of Dynamometer—Forces indicated by Dynamometer—Relative Force of Summer and Winter Gales—Greatest recorded Force in the Atlantic and German Oceans—Forces exerted at different Levels—Proofs of the Accuracy of Results of Dynamometer—Answer to Objection to Results—Answer to Objection of referring Results to a statical Value—Concentrated Action produced by all breaking Waves.

SMEATON, when referring to the propriety of using joggles in the masonry of the Eddystone Lighthouse, says—"When we have to do with, and to endeavour to control, those powers of nature that are subject to no calculation, I trust it will be deemed prudent not to omit in such a case anything that can without difficulty be applied, and that would be likely to add to the security." This statement of our greatest marine engineer indicates the propriety of carefully collecting any facts that may help us to a more accurate estimation of those forces which he regarded as being "*subject to no calculation.*" We shall therefore state a few facts which have been recorded of the destructive power of the waves both in small bodies of water and in the open ocean.

*Inland Lochs.*—At Port Sonachan, in Loch Awe, where the fetch is under fourteen miles of fresh water, a stone

weighing a quarter of a ton was torn out of the masonry of the landing-slip and overturned. Mr. D. Stevenson, in his *Engineering of North America,* describes the harbours in Lake Erie as reminding him of those on our sea-girt shores, and mentions having seen at the harbour of Buffalo one stone, weighing upwards of half a ton, which had been torn out of its bed, moved several feet, and turned upside down. At the Bishop Rock Lighthouse a bell was broken from its attachments at the level of 100 feet above the high-water mark during a gale in the winter of 1860;[1] and at Unst, the most northern of the Zetland Islands, a door was broken open at a height of 195 feet above the sea. To these facts it may be added that I know, from the testimony of an *eye-witness,* of a block of 50 tons' weight being moved by the sea at Barra-head, one of the Hebrides.

*Remarkable Destructive Effects at Whalsey Skerries.*—But still more extraordinary effects have been observed at Whalsey, in Zetland, where heavy blocks of rock have been quarried, or broken out of their beds *in situ* on the top of the Bound Skerry, at a great elevation above the sea. Though there are probably few places where the waves are so violent and dangerous as at Whalsey, still it is well for the reader to be able to recognise the characteristic appearances of similar dangerous localities, and to be put on his guard by a description of the place and the phenomena which it presents, *for it must be distinctly understood that in such places the ordinary methods of construction cannot be applied.* Indeed, it may be questioned whether the stability of works of any kind can reasonably be expected to withstand such forces.

The Bound Skerry is the most eastern of the Shetland group. It consists of quartz rock, forming a part of the

[1] *Nautical Magazine,* vol. xxxi. p. 262.

gneiss strata, which are here permeated to a considerable extent by "dries" or seams, and, with the exception of a species of lichen that grows on the higher parts, little or no vegetation is to be seen on its surface, although it attains at one point an elevation of 80 feet above high-water, and about 86 feet above low-water spring tides. The specific gravity of the rock I found to be 2.698, or about 13.3 cubic feet to the ton. The calculations of the weights of the blocks that were moved I have taken, however, at 14 feet to the ton, in order to be fully within the mark. The accompanying sections

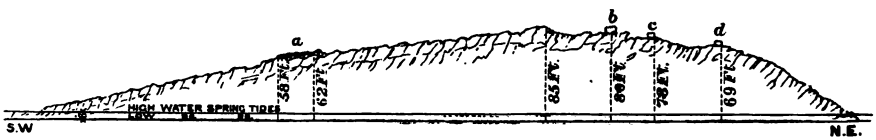


Fig. 7.

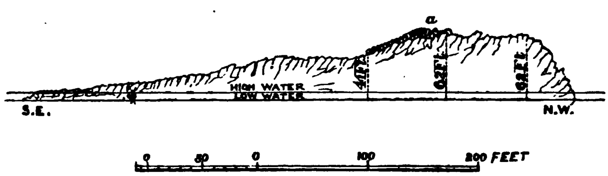


Fig. 8.

(Figs. 7, 8) were made with the spirit-level, and represent elevations of the skerry in the north-eastern and south-western directions, which are the most exposed. It must not, however, be supposed that there is any approach to uniformity of contour, even at places which are very near to each other. The whole island, indeed, forms one of the most rugged and irregular rocks that can well be imagined.

In 1852, when landing for the first time upon this skerry, in order to fix upon the best site for a lighthouse, my attention was speedily attracted by some unmistakable indications

of a violent destructive agency which seemed to have been lately at work upon the hard rock of which it consists. These were the presence of loose blocks of a very large size which had been detached from the adjoining strata. The only visible agent was the ocean, the unruffled surface of which appeared far below the place where I stood—not less, indeed, than 70 feet, as the levels afterwards proved. Under circumstances so unlikely, it will not appear strange that I did not readily persuade myself that the sea was really the agent of destruction. But, after wandering for an hour or more over the surface of this rugged islet, it was impossible any longer to doubt that the remarkable effects which I had noticed were due to the sea alone. I landed on the Bound Skerry with what I thought tolerably certain and definite conceptions, not hastily adopted, but the result of nearly twenty years' study of the action of the waves at different parts of the coasts of Britain ; but I came away with greatly altered views. In order to satisfy myself fully as to the matter I proceeded to the adjoining islands of Gruna and Brury, where at almost every step similar proofs of violent action presented themselves. At Brury, for example, the ground was covered with large recently moved blocks, at an elevation of 45 feet above high-water.

To return, however, to the Bound Skerry, it may be stated that a considerable portion of the rock which confronts the south-eastern round to the north-eastern seas is in a state of rapid disintegration. On the south-east side, about 370 feet from the low-water mark, and at a height of 62½ feet above its level, there occurs a remarkable beach of angular blocks varying in size from about 9½ tons downwards, and huddled together just as one would have expected to find had they been elevated only a few feet above the high-water level.

This beach of stones appears in the sections at *a*, Figs. 7 and 8. A little farther seawards was found a detached block of 19.5 tons.

Towards the north-east, at the level of 72 feet above the sea, in addition to many smaller blocks which had evidently been recently detached, there was one 5½ tons in weight (*b*,

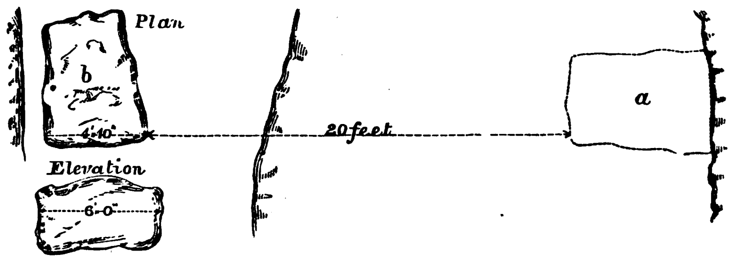



Fig. 9.

Fig. 9). It presented the appearance of recent detachment, having a fresh unweathered look. Within 20 feet of the spot where it lay there was a comparatively recently-formed void in the rock, which, upon examination and comparison by measurement, was found to suit exactly the detached block. Here, then, was a phenomenon so remarkable as almost to stagger belief—a mass of 5½ tons not only moved but actually quarried from its position *in situ* at a level of 72

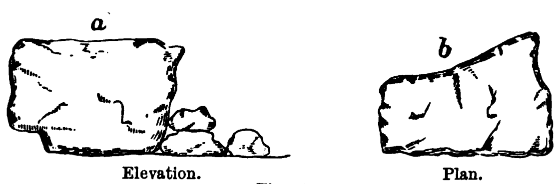



Fig. 10.

feet above high-water spring tides. But higher up still there was another detached rock (Fig. 10), weighing no less than

13½ tons, tilted up in a peculiar position, and underneath which numerous angular masses had been wedged, obviously by aqueous action. This great block (Fig. 10) was, however, unlike the one first described, in bearing no traces of *recent* displacement. Though covered with lichen, and apparently long undisturbed, yet there can be no doubt that it too had been separated from the parent cliff, and been tilted up into the position which it now occupies by no other agency than that of the sea, the high-water margin of which is 74 feet below it.

Some persons have suggested that these effects, which must have been the result of an enormous mechanical power, might have been produced by artificial means, or by lightning, or by some abnormal wave due to volcanic energy. These explanations, however, are altogether untenable; for, without touching upon other objections that might be urged against such hypotheses, the wide-spread and frequent recurrence of similar though not quite so remarkable appearances on the adjoining islands furnishes, to any one who will spend a day in exploring the rocks at Whalsey, abundant proofs that such explanations are quite insufficient to explain the phenomena. In order, however, to remove as far as possible any doubts that may exist as to the waves having been the sole cause of these destructive effects, I shall describe a block which was dis-

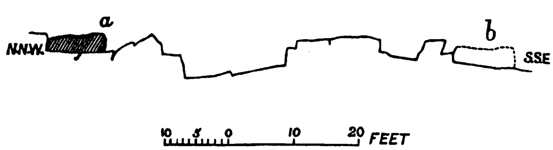


Fig. 11.

covered on a lower rock on the south-east side of the skerry. This mass of 7½ tons, represented in Fig. 11, rested upon

rugged peaks of rock at the level of 20 feet above the sea. That it had been *very recently* detached no one who saw it could for a moment have a doubt. It was wedged against a high ledge of the skerry; and that it had been driven against this obstacle with great violence was proved by the fact that both the block itself and the rock *in situ* were smashed and splintered at the point of contact. All its margins were scored and broken, just as might have been expected from its successive contact with the different ledges of rock over which it had been moved. The original position *in situ, b,* from which it had been detached, is shown by dotted lines. It was easy to trace the course which it had taken, as there were everywhere visible, unmistakable marks of the violence with which it had been driven along its rocky path, which was of the most irregular description, presenting abrupt and almost vertical faces of from 2 to 7 feet in height. At the distance of 11 feet from the block lay loose fragments, one of which required three men to lift, and which was found to fit exactly into a void in the large block. The original position *in situ* was 73 feet distant in a south-south-east direction, and the void was found to agree in every respect with the travelled block both in shape and dimensions. The gale which detached this mass was thus proved to have been from the south-south-east, and the maximum length of "*fetch*" corresponding to this direction is about 500 miles. The natives of the adjoining island told me that it had not been detached when they last landed on the rock.

The fact that a block of nearly 8 tons had been torn up and driven before the waves at the level of 20 feet above the sea for a distance of 73 feet over such rugged ledges, is certainly very remarkable, though it cannot compete with the instances first mentioned, where the masses were from 6 to

13 tons in weight, and had been forced from their original beds at places which are from 70 to 75 feet above the sea. This less remarkable fact is adduced merely with the view of supplying a link in the chain of evidence which connects the sea with the movement of the larger blocks at the higher level. Mr. D. Stevenson has since found similar, though not such remarkable appearances, on other islands on the north-east of Shetland, which led him to the conclusion that these violent effects are generally characteristic of those seas. My last visit to Whalsey having been fortunately made in company with the late Sir Roderick Murchison, I very willingly add the testimony of so distinguished a geologist. He says[1]—"Mr. Stevenson here" (at Bound Skerry) "called my attention to the manifest proofs of the remarkable power of the sea-waves when lashing upon this exposed spot in great storms. The seaward or north-eastern face of the gneissose rocks sloping upwards, presents the most chaotic aspect, being covered with clusters of large angular blocks, one of the largest of these being at nearly 70 feet above the sea. Now, all of them have been torn out of their beds, and most of them moved up-hill for a considerable number of feet, to within a few yards of the base of the new lighthouse. For my own part, I was at first incredulous as to the mode of producing what my lamented friend, Leopold von Buch, would have called a true 'Felsen Meer;' but when Mr. Stevenson brought the data before me, it was quite evident that the sea had done it all. Thus, an inhabitant pointed out some of the chief blocks, several of them many tons' weight, which, in a great storm some years back, had been moved upwards on the incline 15 to 20 feet, to heights of 50 feet above the sea. These, in their upward translation, had scored the rocks over which they passed, just

[1] *Quarterly Journal of the Geo. Soc. of London*, 1859, vol. xv. p. 392.

as the stones held in a glacier groove and scratch in their descent; and the freshness of the markings was quite striking. Not trusting to histories of the past, and for a moment doubting even the clear evidence offered by the scoring of the rugged subjacent rocks, I interrogated an intelligent under-officer of the lighthouse, who had been two years on the spot, and ascertained that, even in the preceding winter, and when the new lighthouse was in course of construction, a huge mass of stone near the sea-level, of which he showed the very bed out of which it had been lifted, had been wrenched out of it, and moved up an incline of 10° or 12° to a distance of 16 feet! and with this proof all scepticism vanished."

*Extraordinary Force of the Sea at Wick Breakwater.*— When we wish to ascertain what is the greatest feat that has been achieved by the waves, we naturally look to the ravages which are to be discovered in the rocky cliffs which confront the ocean. We should never expect that examples of the development of the *greatest* force would be found to be against the masonry of those artificial works which form our ports and harbours. The enormous extent and endless variety of exposure of the shores of Britain, as compared with those of the few piers or breakwaters erected here and there along the line of coast, make it to the last degree improbable that the maximum results should be found anywhere else than among the rocks *in situ* on the shore. Accordingly, the examples of the most violent wave-action which have just been mentioned, and which were all that were given in the first edition of this book, were cases of the destruction or movement of dislocated natural rocks. This, however, no longer holds true. The most startling example now on record is that of an artificial work.

The harbour works at Wick, which were for nine years

in progress before they were abandoned, were commenced in 1863, and consisted of blocks of from 5 to 10 tons, set on edge, first built above high-water neap tides with hydraulic lime, then with Roman, and latterly with Portland cement. Plate No. XI. shows the position and depth of water in which the breakwater is built. In October 1864, 300 feet of the contractor's staging were carried away; and greenheart was afterwards substituted for memel piles. The depth under low-water springs in which the first portion of the wall was founded was 12 feet, in conformity with universal practice; but 18 feet was afterwards adopted, which was a fortunate precaution, for in 1868 the rubble was washed down to 15 feet below low-water, and serious damage occurred to a part of the superstructure. In 1870 a length of 380 feet (about ⅓ of the whole) was destroyed. In February 1872, after the superstructure had been rebuilt solid with Portland cement, a new species of damage took place, the face-stones being in many places shattered by the sea, which is all the more remarkable from the fact that the blocks were of the same density as granite, and of a strength three times greater than that of Craigleith stone—a phenomenon, indeed, unparalleled in the history of sea works. In December 1872, a further proof of force was manifested, and is thus given in the words of a report by Messrs. Stevenson:—"The (seaward) end of the work, as has been explained, was protected by a mass of cement rubble work. It was composed of three courses of large blocks of 80 to 100 tons, which were deposited as a foundation (in a trench made) in the rubble. Above this foundation there were three courses of large stones carefully set in cement, and the whole was surmounted by a large monolith of cement rubble measuring about 26 feet by 45 feet, by 11 feet in thickness, weighing

upwards of 800 tons. This block was built *in situ.* As a further precaution, iron rods, 3½ inches diameter, were fixed in the uppermost of the foundation courses of cement rubble. These rods were carried through the courses of stone work by holes cut in the stone, and were finally embedded in the monolithic mass which formed the upper portion of the pier. The arrangements we have described will perhaps be best understood by the accompanying sketch, Plate XI. Incredible as it may seem, this huge mass succumbed to the force of the waves, and Mr. M'Donald, the resident engineer, actually saw it from the adjacent cliff being gradually "*slewed*" round by successive strokes, until it was finally removed, and deposited inside of the pier. It was not for some days after that any examination could be made of this singular phenomenon, but the result of the examination only gave rise to increased amazement at the feat which the waves had achieved. It was found on examination by diving that the 800-ton monolith forming the upper portion of the pier, which the resident engineer had seen in the act of being washed away, had carried with it the whole of the lower courses which were attached to it by the iron bolts, and that this enormous mass, weighing not less than 1350 tons, had been removed *en masse,* and was resting *entire* on the rubble at the side of the pier, having sustained no damage but a slight fracture at the edges. A further examination also disclosed the fact that the lower or foundation course of 80-ton blocks, which were laid on the rubble, retained their positions unmoved. The second course of cement blocks, on which the 1350 tons rested, had been swept off after being relieved from the superincumbent weight, and some of them were found entire near the head of the breakwater. The removal of this protection left the end of the work open, and the

storm, which continued to rage for some days after the destruction of the cement rubble defence, carried away about 150 feet of the masonry ($\frac{1}{7}$ of the whole), which had been built solid and set in cement. The same remarkable feature of former damage was strikingly apparent in the last damage —*the foundations, even to the outer extremity of the work, remaining uninjured*." Extraordinary as this may appear it was surpassed in 1877, when another concrete mass, which had been substituted for the one that was moved, was in like manner carried away, though it contained 1500 cubic yards of cement rubble, the weight of which was about 2600 tons.

Plate XII. is a photographic view of the breaking waves, taken after the strength of the storm of December 1872 had passed, and for the use of which I am indebted to the kindness of Mr. A. Johnston of Wick, by whom the original photograph was made.

*Marine Dynamometer.*—The value and importance of ascertaining, by direct experiments, the actual force of the waves expressed in pounds per square foot, or some other measure, either statical or dynamical, will readily be admitted. It will, however, require many years' observations before we can expect to have certain information on such a subject, or be enabled to apply the results with confidence in determining the safe limits of construction for marine works. With a view to forward the investigation, the results may be given of some observations which commenced in 1842, at Little Ross Island, off Kirkcudbrightshire, and a detailed account of some of which will be found in the *Edinburgh Transactions*.[1] These observations were made with the marine dynamometer, a simple self-registering instrument which I designed for the purpose.

[1] *Trans. Roy. Soc. Edin.*, vol. xvi. part i. p. 84.

As there is no contest to which the old proverb "*fas est ab hoste doceri*" is more applicable than in opposing the surges of the ocean, it may be proper to give a description of the marine dynamometer, used by the author at many parts of the coast, which will enable any one to have it made.

D E F D is a cast-iron cylinder, which is firmly bolted at the projecting flanges, G, to the rock where the experiments are to be made. This cylinder has a circular flange at D. L is a door which is opened when the observation is to be

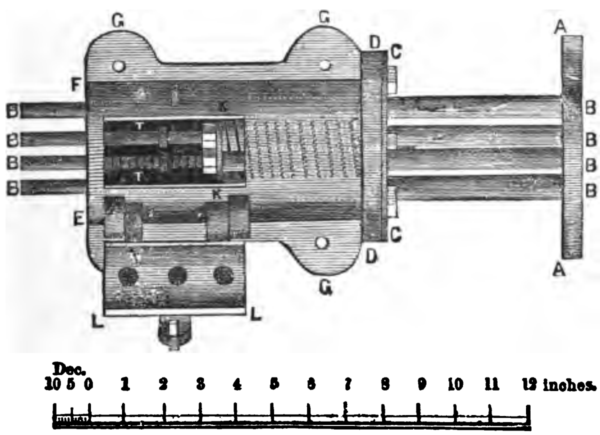



Fig. 12.

read off. A is a circular disc on which the waves impinge. Fastened to the disc are four guide rods B, which pass through a circular plate C (which is screwed down to the flange D), and also through holes in the bottom of the cylinder E F. Within the cylinder there is attached to the plate C a very strong steel spring, to the other or free end of which is fastened the small circular plate K, which again is secured to the guide rods B. There are also rings of leather, T, which slide on the guide rods, and serve as indices for registering

how far the rods have been pushed through the holes in the bottom E F, or, in other words, how far the spring has been drawn out by the action of the waves against the disc A.

The following formula will be found convenient in the graduation of the instrument :—

W = weight stated in tons, which is found by experiment to produce a given amount of yielding of the spring. D = number of inches yielded by the spring with weight W. $a$ = area of the disc in square feet, $d$ = the length in inches on the proposed scale, corresponding to a force of one ton per square foot acting on the disc.

$$d = \frac{\mathrm{D}\,a}{\mathrm{W}}$$

The different discs employed in the observations referred to, were from 3 to 9 inches diameter, but generally 6 inches, and the strength of the springs varied from about 10 lbs. to about 50 lbs. for every $\frac{1}{8}$ inch of elongation, and the instruments varied in length from 14 inches to 3 feet. Their respective indications were afterwards reduced to a value per square foot. The instrument was generally placed so as to be immersed at about $\frac{3}{4}$ths tide, and in such situations as would afford a considerable depth of water. It is not desirable to select a site on a much lower level, as it has not unfrequently happened during a gale that, for days together, no one could approach the dynamometer to read off the result and readjust the indices to zero. It must, at the same time, be remarked, that it is in most situations almost impossible to receive the force unimpaired, as the waves are so often more or less broken by hidden rocks or shoal ground before they reach the instrument.

*Other forms of Dynamometer.*—The instrument which has

been described is probably the most convenient that can be adopted, but I have referred in the *Edinburgh Transactions* to other methods which might in some cases be found more suitable.[1] For example, the impulse of each wave could be noted at such a situation as the Bell Rock or Eddystone Lighthouse by conducting a column of water or air into the interior of the tower. The force of each wave as it struck the building would thus at once be shown either by the rise of the water column, or, if air were used, by means of an attached gauge which would show the same result in atmospheres by compression. The indications of any kind of dynamometer could also be transmitted by wires to some convenient distance, and thus the impulse of every wave could be separately recorded.

*Forces indicated by the Dynamometer.*—With instruments of the kind shown in Fig. 12, a series of observations, commencing in 1843, was made on the Atlantic, at the Skerryvore, and neighbouring rocks, lying off the island of Tyree, Argyllshire; and in 1844 a series of similar observations was begun on the German Ocean, at the Bell Rock.

Referring for more full information to the tables of observations which are given in the *Edinburgh Transactions,* it will be sufficient here to state generally the results obtained, which were as follows :—Only premising that the values refer to areas of limited extent, and are applicable therefore only to the *piecemeal* destruction of masonry, and must not be held as applicable to large surfaces of masonry.

*Relative Force of Summer and Winter Gales.*—In the *Atlantic Ocean,* at the Skerryvore rocks, and at the neighbouring island of Tyree, the average of the results that were registered for five of the summer months during the years

[1] *Trans. Roy. Soc. Edin.*, vol. xvi. part i.

1843 and 1844 was 611 lbs. per square foot = 0.27 ton. The average results for six of the winter months (1843 and 1844) was 2086 lbs. = 0.93 ton per square foot, or more than *three times as great as in the summer months.*

*Greatest recorded Forces in the Atlantic and German Ocean.*—The *greatest result* obtained at Skerryvore was during the heavy westerly gale of 29th March 1845, when a force of 6083 lbs., or nearly three tons per square foot on the surface exposed was registered. The next highest was 5323 lbs.

In the *German Ocean* the greatest result obtained at the Bell Rock on the surface exposed was at the rate of 3013 lbs. per square foot. But subsequent and much more extended observations at Dunbar, in the county of East Lothian, gave 3½ tons; while at the harbour works of Buckie, on the coast of Banffshire, the highest result of observations extending over a period of several years, was three tons per square foot.

*Forces exerted at different Levels.*—An exposed part of the Skerryvore rock was also chosen, on which two instruments were fixed, the one (No. I.) several feet lower, and about 40 feet seaward of the other (No. II.). It was observed that about half-flood the force of the waves was a good deal expended before they reached the spot where No. I. was placed, from there being so little water on the rocks outside. Whereas, when the tide was higher, the waves were, from the greater depth of water, not so much broken when they reached No. II. The results show generally about *twice* the force at No. II. as at No. I.; a fact which proves how important it would be to ascertain the relative forces of the waves at different levels upon our breakwaters and other sea works.

The observations at Dunbar and Buckie prove that the sea may exert a force so great as 3½ *tons over the limited extent of surface presented by the discs,* and that the force varies

much with the level at which the instruments are fixed. These results are given, however, not as ultimate data for calculation, but simply as determining the fact that the sea has been known to exert a force equivalent to a pressure of $3\frac{1}{2}$ tons per square foot, *however much more.* There can be no doubt that results higher than these may yet be obtained.

| Date. | Remarks. | No. of Instrument. | Pressure in lbs. per Square Foot. |
|---|---|---|---|
| 1845. | | | |
| Jan. 7. | Heavy Sea. | I. | 1714 |
| „ „ | „ | II. | 4182 |
| „ 12. | Very heavy swell. | I. | 2856 |
| „ „ | „ „ | II. | 5032 |
| „ 16. | Heavy ground-swell. | I. | 2856 |
| „ „ | „ „ | II. | 4752 |
| „ 22. | A good deal of sea. | I. | 2856 |
| „ „ | „ „ | II. | 5323 |
| „ 28. | Heavy ground-swell. | I. | 2627 |
| „ „ | „ „ | II. | 4562 |
| Feb. 5. | Fresh gales. | I. | 856 |
| „ „ | „ | II. | 3042 |
| „ 21. | „ | I. | 1827 |
| „ „ | „ | II. | 3422 |
| „ 24. | Fresh breezes. | I. | 1256 |
| „ „ | „ | II. | 3802 |
| March 9. | Ground-swell. | I. | 1256 |
| „ „ | Waves supposed about 10 feet high. | II. | 3041 |
| „ 11. | Short sea. | I. | 1028 |
| „ 24. | Heavy sea. | I. | 2281 |
| „ „ | Waves supposed about 20 feet high. | II. | 4562 |
| „ 26. | Swell. | I. | 1256 |
| „ „ | Waves about 6 feet high. | II. | 3041 |
| „ 29. | Strong gale, with heavy sea, the highest waves supposed 20 feet high, | I. | 2856 |
| | and the spray rose about 70 feet. | II. | 6083 |

Were the observations sufficiently multiplied we should soon obtain data which would be highly useful in practice, as they would, by reference to existing sea works, show what sizes of stones or concrete blocks were necessary for resisting any given force that was indicated by the dynamometer.

*Proofs of the Accuracy of the Results of the Dynamometer.*—The greatness of the forces recorded by the dynamometer has led some to express doubts as to the accuracy of the results. This is not to be wondered at, for prior to these observations very erroneous ideas were entertained of the impulsive force of the sea. Sir Samuel Brown, for example, in his arguments for adopting bronze lighthouses[1] takes the force "on each cylindrical foot column," at only 80 lbs. Captain Taylor, in advocating his proposed plan for floating harbours of refuge,[2] allows a pressure of 144 lbs. per square foot, and Minard seems to calculate on only 70 lbs. per square foot.

The doubts that have been expressed were based on the assumption that the action of the waves is the same as the impact of a hard body; and on the objection to expressing a dynamical force by a statical value. Three classes of phenomena, essentially different from each other, may be referred to as proofs that if the indications of the dynamometer do not represent the force actually exerted, the error must be in defect and certainly not in excess. These are—1st, The displacement of heavy bodies, proofs of which have already been given; 2d, the elevation of spray; and 3d, the fracture of materials of known strength. The elevation of the spray at the Eddystone, the Bishops, and the Bell Rock Lighthouses,

[1] *Description of a Bronze or Cast-Iron Columnal Lighthouse designed for the Wolf Rock or the Skerryvore,* by Sam. Brown, Esq., R.N., K.H. Edinburgh, 1836, p. 14.

[2] *Plans for the Formation of Harbours of Refuge,* by Captain T. N. Taylor, R.N., C.B. Plymouth, 1840, p. 7.

is well known. In November 1827, during a ground-swell, *without wind*, the water rose to the gilded ball on the top of the Bell Rock lantern, which is 117 feet above the rock, and as the tide on that day rose 11 feet on the tower, this leaves 106 feet as the height of elevation. On the same day a ladder was broken from its attachment to the balcony at an elevation of 86 feet, and washed round to the other side. It therefore follows that there is a force in action at the foot of the Bell Rock tower competent during ground-swells, when *there is no wind*, to project a column of water to the height of 106 feet, which, according to the laws of hydrodynamics, is due to a pressure of very nearly three tons per square foot, —whereas the greatest force that happens to have been actually recorded by the dynamometer at this place was only 1½ ton.

Beams of Memel timber, called Booms (*vide* Chap. VIII.), which are used at Hynish Harbour, Argyllshire, for keeping the sea out of a small tide basin, have been very frequently broken by the waves. They were 20 feet long between the supports, and 12 inches square. Within six years after the harbour was completed, and at different dates, seven of them were broken, though they were of perfectly sound quality. Each of these logs would resist fracture though uniformly loaded with a weight of 30 tons, so that the sea at Hynish must, on seven different occasions, have exerted a force on each boom which may justly be compared to a dead weight of 30 tons uniformly distributed over the logs. Dynamometric observations were made at Hynish for a considerable time, and the highest result recorded at that place was 1⅛ ton per square foot, whilst the pressure required to break the booms must have been at least 1½ ton per foot of surface exposed. At Pulteneytown Harbour works, which have been already referred to, both Memel and greenheart logs, placed vertically

in the sea, were found altogether insufficient for the contractor's staging, having been invariably broken near the level of high-water. For the satisfaction, however, of any who may still have doubts as to the action of this instrument, the following Table is added, which contains simultaneous observations made at Skerryvore with three dynamometers, having not only discs of very different areas but springs of very different powers, and yet the results are almost identical :—

TABLE of OBSERVATIONS made at SKERRYVORE ROCKS, and also at the ISLAND of TYRII, with three Dynamometers, having springs of different strength, and discs of different sizes, fixed parallel and close to each other :—

| Dates. | Lbs. to a Square Foot. | Dates. | Lbs. to a Square Foot. | Dates. | Lbs. to a Square Foot. |
|---|---|---|---|---|---|
| 1844. | | 1844. | | 1844. | |
| Jan. 16 | 428 | Mar. 4 | 3369 | April 16 | 642 |
| ,, ,, | 427 | ,, ,, | 3427 | ,, ,, | 481 |
| ,, 28 | 3422* | ,, 7 | 1069 | ,, 17 | 800 |
| ,, ,, | 2285* | ,, ,, | 963 | ,, ,, | 856 |
| ,, ,, | 3313 | ,, ,, | 913 | ,, ,, | 962 |
| Feb. 2 | 429 | ,, 10 | 1925 | ,, 18 | 571 |
| ,, ,, | 457 | ,, ,, | 1925 | ,, ,, | 481 |
| ,, 3 | 429 | ,, ,, | 1713 | ,, 19 | 800 |
| ,, ,, | 457 | ,, 11 | 535 | ,, ,, | 535 |
| ,, 13 | 214 | ,, ,, | 481 | ,, ,, | 481 |
| ,, ,, | 228 | ,, ,, | 456 | ,, 22 | 913 |
| ,, 15 | 321 | ,, 12 | 3316 | ,, ,, | 428 |
| ,, ,, | 280 | ,, ,, | 4011 | ,, ,, | 962 |
| ,, ,, | 321 | ,, ,, | 2970 | ,, 24 | 1942 |
| ,, 16 | 428 | ,, 13 | 1142 | ,, ,, | 1604 |
| ,, ,, | 402 | ,, ,, | 1283 | ,, ,, | 1370 |
| ,, ,, | 343 | ,, ,, | 1283 | ,, 25 | 1283 |
| ,, 24 | 1284 | April 10 | 457 | ,, ,, | 343 |
| ,, ,, | 1364 | ,, ,, | 428 | ,, ,, | 321 |
| ,, ,, | 685 | ,, ,, | 481 | ,, 27 | 457 |
| ,, 26 | 2032 | ,, 11 | 800 | ,, ,, | 481 |
| ,, ,, | 2086 | ,, 12 | 343 | ,, ,, | Night tide 800 |
| ,, ,, | 399 | ,, ,, | 321 | | |
| ,, 27 | 321 | ,, 14 | 571 | ,, ,, | 642 |
| ,, ,, | 321 | ,, ,, | 535 | ,, 30 | 229 |
| ,, ,, | 342 | ,, 16 | 571 | ,, ,, | 241 |
| Mar. 4 | 3316 | | | | |

*Note.*—The two marked thus* were too weak, as the leathers were found flattened, and one of the instruments was broken and was not repaired till the 15th February.

*The means of the above nine observations, which were made with only two instruments, are* 433 *lbs. and* 415 *lbs. respectively.*

*The means of the above eighteen observations, which were made with three instruments, are* 1247 *lbs.,* 1183 *lbs., and* 1000 *lbs. respectively.*

*Answer to the Objection that the Action of the Waves is the same as the Impact of a Hard Body.*—Now the same force, supposing the waves to act like the impact of a hard body, would, in the marine dynamometer, assume very different statical values, according to the spaces in which that force was expended or developed, so that, with the same force of impact, the indications of a weak spring would be less than that of a stronger. This appears from the annexed Table, which contains results of a few experiments in which the springs were tested dynamically by the impact of a cannon-ball dropped from a given height upon the disc of each instrument, which was fixed vertically in a framework of timber, with the disc uppermost. It will be seen from the Table, as was to have been expected, that within the limits of the experiments there was for each spring a different ratio between the value registered by the leather index and the calculated momentum of the falling body. If the waves acted by a sudden finite impact like the cannon-ball, we should not have found such harmony between the results of springs of different strength as appears in the Table of Observations at Skerryvore. *The action of a wave, therefore, is not momentary, as in the case of a solid, but is continuous during the period that the disc is immersed in the passing wave.* In short, to make the cases analogous, a continuous succession of cannon-balls should fall on the disc.

TABLE representing Experiments made on the impact of a Cannon-Ball upon Dynamometers having springs of different strengths.

| Large Dynamometer. Strength of spring 462.24 lbs. per inch of elongation. Falling weight 32.5 lbs. | | | | | |
|---|---|---|---|---|---|
| 1<br>Height fallen through by Cannon-Ball, in Feet. or $h$. | 2<br>Spring elongated in Inches. $e$ | 3<br>Calculated Velocity at impact in feet per second. $v=\sqrt{h+e}$ | 4<br>Calculated Momentum. | 5<br>Registered Pressure. | 6<br>Registered Pressure. ÷ Momentum. |
| 0.5 | 0.875 | 5.67 | 184.3 | 404.5 | 2.195 |
| 1.0 | 1.25 | 8.02 | 260.7 | 577.8 | 2.216 |
| 1.5 | 1.5 | 9.83 | 316.5 | 693.4 | 2.191 |
| 2.0 | 1.685 | 11.35 | 368.9 | 779.4 | 2.113 |
| | | | | Mean | 2.179 |
| Small Dynamometer. Strength of spring 156 lbs. per inch of elongation. Falling weight 32.5 lb. | | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 |
| 0.5 | 1.5 | 5.67 | 184.3 | 234 | 1.270 |
| 1.0 | 2.0 | 8·02 | 260.7 | 312 | 1.197 |
| | | | | Mean | 1.233 |

Hence it follows that within the limits of the experiments the momentum with the strong spring = $\left\{\dfrac{\text{Registered Pressure}}{2.179}\right.$

Whereas with the weak spring the momentum = $\left\{\dfrac{\text{Registered Pressure}}{1.233}\right.$

*Answer to the Objection to referring the Results of a Dynamical Force to a Statical Value.*—The objection which has been raised against any statical valuation of the dynamical effect of the waves falls to the ground when we remember that in all sea works we oppose the dynamical action of the sea by the *dead weight or inertia* of the masonry, so that the dynamometer furnishes exactly the kind of information which the engineer requires.

*Concentrated Action produced by all breaking Waves.*—Although the height of a jet of water will be increased if the obstacle be of a converging form, yet any plane vertical barrier will produce a high jet, for we see it in every sea-wall, and with all conceivable configurations of bottom. The phenomenon is indeed far too common to admit the supposition of its being occasioned by any re-entrant angle in the bottom, but is probably due to the manner in which a breaking wave collapses or curls over upon itself. From observations which I repeatedly made on the shores of the Mediterranean, at a place where the beach, which was gravelly, presented a uniform profile, the filaments of the waves in breaking were found to converge very symmetrically, and although there was no obstacle but the beach, the spray was invariably raised much higher than the level of the crest of the unbroken wave. This peculiar change of form, which is common to all breaking waves, destroys the parallelism which may have previously existed among any of the moving filaments of fluid, and converges them towards a horizontal axial line, so that the particles at and near such line are driven upwards not only with their own original velocity, but with an increased velocity due to the proportion subsisting between the number of particles that are raised and the greater number of particles that are finally stopped.

Some measurements of the height of spray against sea-walls will be found in a subsequent chapter.

The following Table, by the late Professor Rankine,[1] gives examples of heights in feet due to velocities in feet per second as computed by the equation—

$$\text{Height in feet} = v^2 \div 64.4.$$

[1] *A Manual of Civil Engineering*, by W. J. Macquorn Rankine, p. 676, Lond., 1862.

It is exact for latitude $54\frac{3}{4}°$, and near enough to exactness for practical purposes in all latitudes.

| *v.* | Height. | *v.* | Height. | *v.* | Height. | *v.* | Height. | *v.* | Height. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .015528 | 17 | 4.4875 | 32.2 | 16.100 | 48 | 35.776 | 76 | 89.688 |
| 2 | .062111 | 18 | 5.0310 | 33 | 16.910 | 49 | 37.282 | 78 | 94.471 |
| 3 | .13975 | 19 | 5.6055 | 34 | 17.950 | 50 | 38.819 | 80 | 99.377 |
| 4 | .24844 | 20 | 6.2111 | 35 | 19.021 | 52 | 41.987 | 82 | 104.41 |
| 5 | .38819 | 21 | 6.8477 | 36 | 20.124 | 54 | 45.279 | 84 | 109.56 |
| 6 | .55900 | 22 | 7.5153 | 37 | 21.257 | 56 | 48.695 | 86 | 114.84 |
| 7 | .76086 | 23 | 8.2141 | 38 | 22.422 | 58 | 52.235 | 88 | 120.25 |
| 8 | .99377 | 24 | 8.9439 | 39 | 23.618 | 60 | 55.900 | 90 | 125.77 |
| 9 | 1.2577 | 25 | 9.7048 | 40 | 24.844 | 62 | 59.688 | 92 | 131.43 |
| 10 | 1.5528 | 26 | 10.497 | 41 | 26.102 | 64 | 63.601 | 94 | 137.20 |
| 11 | 1.8789 | 27 | 11.320 | 42 | 27.391 | 64.4 | 64.400 | 96 | 143.10 |
| 12 | 2.2360 | 28 | 12.174 | 43 | 28.711 | 66 | 67.639 | 98 | 149.13 |
| 13 | 2.6241 | 29 | 13.059 | 44 | 30.062 | 68 | 71.800 | 100 | 155.28 |
| 14 | 3.0434 | 30 | 13.975 | 45 | 31.444 | 70 | 76.086 | | |
| 15 | 3.4937 | 31 | 14.922 | 46 | 32.857 | 72 | 80.496 | | |
| 16 | 3.9751 | 32 | 15.900 | 47 | 34.301 | 74 | 85.029 | | |

## CHAPTER V.

### CONDITIONS WHICH AFFECT THE FORCE OF WAVES.

Tides sometimes act as Breakwaters—Causes of Roosts or Races—Velocity of British Races—Bars of Rivers form miniature Races—Tides sometimes increase surf on Shore—Time of Tide when Surf is heaviest—Characteristics of Coasts which are affected by Tides—Relation between Height of Waves and Depth of Water—Depth regulates Height of Waves—Depth in which Waves break—Height of Waves above Mean Level.

*The Tides in some cases act as Breakwaters to the Shore.*—At some parts of the coast the tides cause waves of an unusually dangerous character, while at others they are found to *run down* the sea. If a harbour work were situated in a *race* or rapid tide-way—such, for example, as those called "roosts" in Orkney and Shetland—the masonry would be exposed to the action of a very trying and dangerous high-cresting sea. As an instance, we may refer to Portpatrick in Wigtownshire, where the violence of the waves is, to a great extent, due to the rapidity of the tides. If, on the other hand, the race or roost runs in such a direction as to be *entirely outside of the harbour and at some distance off*, it will, while it lasts, have a decided tendency to shelter the works, by acting as a breakwater. It was proved by observations made specially for the purpose at Sumburgh Head in Shetland during a south-westerly storm, that so long as the Sumburgh Roost (one of the most formidable in those seas, and more than three miles in width) was cresting and breaking heavily outside there

was comparatively little surf on the shore; but no sooner did the roost disappear towards high water, than a heavy sea rolled towards the land, rising on the cliffs to a great height.

The lightkeeper at Sumburgh Head, in a letter to me, says: "We had a very severe gale from the south-west yesterday, and being the first gale we have had, from that quarter, since you were here, I paid particular attention to the state of the sea in the West Voe through the day. By daylight in the morning it was blowing very hard, with a most terribly heavy sea *rolling into the West Voe and breaking over the top of the banks, while low water lasted.* But with regard to what you said to me about the tide in the 'roost' acting as a breakwater to the Voe, your opinion is right, for during the last hours of flood,[1] and the first two hours of ebb tide in particular, *a small boat could have gone till within a few yards of the roost between the Lighthouse and the Horse Island, although the sea was still in the same raging state between the roost and as far as the eye could reach towards Fair Isle and away to the west.*" Here, then, is very satisfactory evidence that the heavy waves were so much reduced in height by breaking in deep water (it is believed not less than about forty fathoms), that when they reached the shore they were nearly harmless. The modifying and intensifying effects of tide currents on waves seem to have been entirely overlooked in the discussions regarding the merits of vertical and sloping walls; a subject which will be referred to in another section.

*Causes of Roosts or Races of the Tide.*—The opinion expressed by a writer in the *Edinburgh Philosophical Journal*—that the cause of races or roosts is merely the meeting of two rapid currents, seems to be erroneous; neither does it appear possible that they are occasioned only by the projec-

[1] The current turns one hour and a half before high water on the shore.

tion of rocks from the bottom of the sea, as many sailors suppose.

From careful inquiries, as well as from actual personal experience of such dangerous breaking waters as the Boar of Duncansby, and the Merry Men of Mey in the Pentland Firth, it appears that the true cause of these dangers is the encounter between the *swell of the ocean and an opposing tidal current.* Two rapid tides may meet each other without any dangerous effects, if there be no ground-swell, yet, if they join together in a rough sea, as in coming round the islands of Stroma or Swona in the Pentland Firth, during ground swells, the effect of their union being to increase the current, highly dangerous waves will be produced. The meeting of the currents, therefore, though not the *cause* of the waves, is nevertheless sure to increase their height, and to make them break. The races which occur in open seas—as, for instance, off headlands and turning-points of the coast—are certain portions of those seas in which, with a ground-swell, the waves break to a greater or less extent, although the water may be very deep, and there may be no wind at the time. At all such places it will be found that there are rapid tides, and that the *breaking waves are produced when the tide runs against a ground-swell.* The roosts, on the west coast of Orkney or of the Pentland Firth, for example, are worst with *ebb* tides and *westerly* swells, because the Atlantic swell and current of ebb are opposed. Those again on the east coast are worst with *flood* tide and *easterly* swells, because the swell from the German Ocean and current of flood are opposed. Thus, at the east end of the Pentland Firth the Boar of Duncansby is well known to rage with easterly swells and a flood tide ; whereas, at the west end of the same firth, the Merry Men of Mey are worst with ebb tide

and a westerly swell, at which time no boat can enter them without the greatest risk of being swamped. One or two quotations from the "Sailing Directions for the Pentland Firth," which are given in the *North Sea Pilot* for 1875, will give the reader a good idea of the dangers of those troubled waters, and of the peculiar phenomena presented by the roosts.

"Before entering the Pentland Firth, all vessels should be *prepared to batten down*, and the hatches of small vessels ought to be secured, *even in the finest weather*, as it is difficult to see what may be going on in the distance, and the transition from smooth water to a broken sea is so sudden that no time is given for making arrangements." "The *Swilkie* (of Stroma) must be avoided by boats even in the finest weather, for a few years since a boat was drawn down by one of the whirlpools, and all her crew perished." "So distinct is the line of demarcation between the stream and the eddy, that in passing in a steamer from the one into the other, the engines are brought to a standstill and the vessel twisted round with a great velocity." "During the flood-stream in an easterly or south-easterly gale, it is absolutely necessary to keep an offing of six to eight miles abreast of the Pentland Skerries, until the flood-stream has ceased. Three vessels were observed to founder, on the 18th August 1848, when attempting, under these circumstances, to run against the flood."

*Velocity of different British Races.*—It will not appear surprising that such effects are produced, when the swiftness of the currents in those northern seas is taken into account. I have collected in a tabular form the velocities of some of the most remarkable races, from which it will be seen that the velocity of one off the Pentland Skerries is nearly *double* that of the well-known "Race of Portland."

| Names of Places. | Authorities. | Velocity at Spring Tides in statute miles per hour. |
|---|---|---|
| Portland Race . . . . | Admiralty Channel Pilot | 5.75 to 6.9 |
| Open ocean between Orkney and Zetland . . . . | Admiralty North Sea Pilot | 5.76 |
| Hoy Sound, Orkney . . | Do. do. | 6.90 |
| Holm Sound, do. . . . | Do. do. | 6.90 |
| Sumburgh Roost, Zetland . | Do. do. | 8.06 |
| Burger Roost, Orkney . . | Do. do. | 8.06 |
| Helgate, New York, east current | Prof. H. Mitchell . | 8.5 |
| Doris Mor, Argyllshire . . | Captain Bedford, R.N. . | 9.22 |
| Gulf of Corrie Vreckan, Argyllshire . . . . . | Do. | 9.83 |
| Roost near Lother, Pentland Firth . . . . . | Admiralty North Sea Pilot | 10.36 |
| Roost near Swona, Pentland Firth | Do. do. | 10.36 |
| Roost near Pentland Skerries . | Admiralty Survey . | 12.20 |

*Bars at the Mouths of Rivers form miniature Races.*—The dangerous surf, which exists at the mouths of some rivers, is not due solely to the want of depth at the bar, but in a great measure to the meeting of the outward current with the waves of the sea, which here form a kind of miniature *roost.* It may therefore be, in some rare cases, an evil to increase the amount of backwater, if the effect would be to increase the current. The velocities at the entrance of some of our British rivers are given in the following Table :—

| Names of Places. | Authorities. | Statute miles per hour. |
|---|---|---|
| The Esk near Montrose . . | North Sea Pilot . | 7.51 |
| Mersey, between Seacombe and Prince's Dock . . . | Baines, Liverpool | 6.75 |
| Humber . . . . . | North Sea Pilot . | 4.7 |
| Queensferry passage, Firth of Forth . . . . . | Messrs. Stevenson | 3 to 4 |
| Clyde at Greenock, last ¼ ebb . | Do. do. | 3.33 |
| The Tay near Buddonness . | Admiralty Pilot . | 2.88 |
| Mersey, Formby . . . | Denham . . | 2.75 |
| Dee abreast of Helbre . . | Admiralty Chart | 3.5 |
| Wear, Sunderland . . . | T. Meik . . | Springs 2.0 |
| Tyne . . . . . . | Mr. Messent, C.E. | Neaps 1.31 |
| Do. . . . . . . | ... ... | Springs 1.79 |
| Ayr . . . . . . | ... ... | .33 |

When a swell encounters a rapid opposing current, the onward motion of the waves is arrested and their length is visibly decreased. They get higher and steeper, crest, and at last break, sometimes very partially, and at other times almost as they would on a shelving beach. It is probable that in such disturbed waters several waves may ultimately combine into one very large billow; for one wave may have its onward motion so much checked as to allow the wave behind to overtake it, and the two having thus coalesced, may, as one large wave, acquire a superior velocity, so as to overtake those in front.

*The Tides sometimes increase the Surf on the Shore.*—It is probably to the velocity of the tide currents, among other causes, that such wonderful effects as those at Whalsey and Wick, already noticed, may be referred. Were such violent action common to all the shores of the German Ocean, instead of being fortunately restricted, as it is, to places where the depth of water is great and the currents strong, some of our eastern seaport towns would, from their low level, be destroyed during the first stormy winter.

*Time of the Tide at which the Surf is heaviest.*—As a further proof of the great effect of the tides on the waves, it may be stated that the time when most damage is done to sea works which are in tolerably deep water is generally from *one to two hours before and after high water.* Murdoch Mackenzie, the justly celebrated marine surveyor and hydrographer of the last century, in speaking of the tides of the Orkney Islands, tells us that "the spring tide acquires a considerable degree of strength in less than one hour after its quiescent state begins. Neap tides are hardly sensible in two hours after still water. The stream is most rapid commonly between the third and fourth hours of

the tide."[1] On the 15th February 1853, during a gale from the north-east, a large body of water was thrown upon the lantern of Nosshead Lighthouse, Caithness-shire, being a height of 175 feet above the sea. This occurred *one hour before high water.* On the 23d November 1824, *one hour and a half before high water,* a very alarming wave struck the Eddystone tower, and enveloped the house to a most unusual extent. The mass of water elevated by this wave broke five panes of the lightroom glass. At Alderney Harbour, Mr. John Jackson, who was the contractor for the works, says "the heaviest seas and the greatest rush of water over the wall occurred an hour after high water."[2] Another remarkable instance occurred at Peterhead Harbour, which projects prominently into the sea on an isthmus, where the tides, at but a short distance seaward of the harbour, run very rapidly. On the 10th January 1849, there was a tremendous sea on the shore, and a crowd of people were down, about *two hours before high water,* helping to secure the whalers and other vessels lying at the quays, when three successive waves, bursting over the harbour, carried away 315 feet of a bulwark founded 9½ feet above high-water springs, and which had stood for many years. One piece of this wall, weighing 13 tons, was moved to the distance of 50 feet. After this violent outbreak of the sea the waves became more moderate, until about *two hours after high-water,* by which time the large whalers had taken the ground, when other three enormous waves again burst over the seaward pier, knocked down the protecting wall, and occasioned the loss of sixteen people, who were washed off the pier. These waves filled the harbour to such a depth as to set all the whalers afloat

[1] *Orcades,* by Murdoch Mackenzie. London, 1750, p. 4.

[2] *Min. Inst. Civ. Eng.,* vol. xxxvii.

again, and they continued so for several minutes, until the excess of water had run out through the harbour mouth.

*Characteristics of Coasts, the Exposures of which are much affected by the Tides.*—From what has been adduced in this and another chapter, the following conclusions seem to be warrantable :—

1. The waves are most destructive when they come in at right angles to the shore-line.

2. Their power is increased in proportion as the direction of the main body of the tide approaches to coincidence with the direction of the heaviest swell; and they are probably worst at those headlands on which the tide splits.

3. Where a considerable part of the coast retires, there will be less sea during the strength of the tide, even although the waves come in at right angles to the shore, because the tide keeps outside, following the direction of the general *trend* of the coast. But this will probably not hold true of *small* re-entrant hollows of the shore.

4. Although the line of exposure and the tide-current are parallel to the coast, yet, if the strength of the tide runs *very near* to the shore, as is the case in short narrow channels, where the velocity of the current is increased, there may, nevertheless, be an unusually heavy sea.

5. The shores which are most severely tried will probably be those where the line of maximum exposure is at right angles to the line of shore, and where it coincides with the direction of the principal tide-current.

I should not have dwelt at such length on this subject, were it not that I might again refer to some of the facts, when treating of the subject of vertical and sloping walls for harbours of refuge, where it is of importance to show that

even in the deepest water the waves are not, at all times, purely oscillatory, but that, wherever there is a tide-current, the waves will more or less partake of the properties of waves of translation.

*Relation between Height of Waves and general Depth of the Sea adjoining.*—Another circumstance affecting the exposure of any marine work is the depth of the sea or ocean on the shores of which it is built. The great rolling billows, so commonly met with in the Atlantic, cannot be generated in the shallower parts of seas like the German Ocean, unless, perhaps, in such peculiar circumstances as have just been adverted to.

Mr. D. Stevenson, in 1838, in his *Engineering of North America,*[1] gave it as his opinion that "to the production of considerable undulations, capable of injuring marine works or endangering their stability, three conditions were necessary :—*First,* That the sheet of water acted upon by the wind shall have a considerable area. *Second,* That its configuration shall be such that the wind moving over it, in any direction, shall act upon its surface extensively, both in the directions of length and breadth. And, *Third,* That the depth of water shall be considerable, and unobstructed by shoals, so as to permit the undulations to develop themselves, to a great extent, without being checked by the retardations caused by shallow water and an unequal bottom."

In a paper read before the Royal Society of Edinburgh, in 1859,[2] I attempted to show, in accordance with those views, that one cause of the peculiarly heavy waves which fall upon the Bound Skerry of Whalsey was not only the great depth

[1] *Engineering of North America,* by D. Stevenson. London, 1838, p. 67.

[2] *Proc. of Royal Society of Edin.*, vol. iv.

of water close to that rocky islet, but the great depth of the German Ocean in those northern latitudes as compared with its southern portions. But as the reduction in the height of the undulations caused by shallow water will be again referred to, I shall only here advise the reader, when judging of any locality, not to confine his attention to the *local* depth which exists immediately in front of the harbour, but to bear in mind the *general depth* of the sea or ocean on the shores of which his work is to be placed. As examples of the differences in this respect, the following instances are given of different harbours on the same coast:—

| Deepest Water at | ½ a mile off the Coast. | 1 mile off the Coast. | At the Works at low water. |
|---|---|---|---|
| Sunderland | 27 feet | 52 feet | 4 feet. |
| Tyne | 30 ,, | 70 ,, | |
| Dunbar | 36 ,, | 78 ,, | |
| Aberdeen | 36 ,, | 102 ,, | |
| Peterhead | 144 ,, | 162 ,, | 7 ,, |
| Wick | 102 ,, | 135 ,, | 34 ,, |

The effective nature of loose particles of sand in checking the sea is referred to in the following curious passage from the Prophet Jeremiah: "Will ye not tremble at my presence, which have placed the sand for the bound of the sea by an everlasting ordinance which it cannot pass: and though the waves thereof toss themselves, yet can they not prevail; though they roar, yet can they not pass over it?"[1]

*Depth in front of a Harbour regulates the Height of the Waves—Largest Waves not always the most destructive.*—If the shoal water, immediately in front of a harbour, extends seawards for a considerable distance, so as to form an extensive flat beach or foreshore, that depth does become the true limit for the maximum wave, whatever may be the

[1] Jeremiah v. 22.

general depth of the sea outside. At Arbroath, for example, Mr. Leslie found that the works were in general not so severely tried by the very heaviest class of waves as by others of lesser size. The small depth over the outlying rocks had the effect of *tripping* up the heavier seas, so as to destroy them before they reached the harbour, while it was still sufficient to allow the smaller waves to pass over the shoals and reach the works in an unbroken state. In like manner, at the River Alne, on the Northumberland coast, it is observed that the smaller waves occasion a greater range in the harbour than those larger ones which break outside, and are therefore reduced in passing over the bar.[1] It thus appears that *the largest waves are not in all places so destructive as smaller ones.* We may also conclude that, in cases of severe exposure, where it would not interfere with the passage of ships, the waves might to a certain extent be reduced by dropping very large blocks of stone or concrete at some distance seawards of the works, so as, by forming an artificial shoal, to cause the waves to crest and break outside. In connection with this subject we may state Mr. J. T. Harrison's opinion, that "during violent on-shore gales the water is altogether raised, so that the medium line between high and low water is sometimes raised several feet. The greatest encroachment upon the beach will, on such occasions, take place during neap tides, for it gives the greatest depth of water over the foreshore at low water."[2]

It is quite possible, in certain cases, that there may be a very considerable depth at low water close to the pier, arising from the geological formation, or due to the scouring action of a local current, while the general character of the

[1] *North Sea Pilot*, Part iii. p. 31. Lond. 1858.

[2] *Min. Civ. Eng.*, vii. 343.

sea outside may be that of a shallow basin, encumbered with reefs or sandbanks, which render the formation of heavy billows altogether impossible.

*Depth of Water in which Waves break.*—It is of great importance to be able, in all cases, to ascertain the maximum possible wave, that can exist, unbroken in any given depth of water. Mr. Scott Russell, whose observations, on what may be called the marine branch of hydrodynamics, are of such great value, has stated that "he has never noticed a wave so much as 10 feet high in 10 feet water, nor so much as 20 feet high in 20 feet water, nor 30 feet high in 5 fathoms water; but he has seen waves approach very nearly to those limits." It is presumed that the datum here referred to is the mean level of the surface of the sea. As the subject is very important—because the depth of water for some distance in front of a work may be said to be the ruling element which determines the amount of force which it has to resist, whatever be the line of exposure, I shall mention some results that I have obtained on this subject:—

OBSERVATIONS made at the Firth of Forth on Breaking Waves on a sandy beach.

| Total Height of Wave. | | Depth of Water in Hollow of Wave. | |
|---|---|---|---|
| Ft. | In. | Ft. | In. |
| 2 | 6 | 1 | 2 |
| 3 | 0 | 1 | 5 |
| 3 | 0 | 1 | 5 |

It must, however, be borne in mind that these observations, and I conceive also those of Mr. Russell, apply only to those

short, steep, and superficial waves, which are due to an existing wind; and not to the ground-swells which are almost constantly to be found in the open ocean, and may be the result of former gales, or are the telegraph, as they have been called, of those yet to come.

Since the first edition of this book was published I had an opportunity, in July 1870, to make observations during a north-easterly ground-swell.[1] The heights could be measured with very considerable accuracy on the iron piles and open sloping slip or grating at the seaward end of the new iron pier at Scarborough.

The following are the results of breaking waves from hollow to crest:—

Heights.
5′ 6″
5 0
5 0
5 6
———
5′ 3″ = mean height.

The mean depth of water below the trough was 10 ft. 3 in.

Heights of the highest breaking waves from hollow to crest:—

6′ 0″
6 0
8 0
6 0
6 0
———
6′ 5″ mean height of highest waves from

[1] *Nature*, August 9, 1872.

hollow to crest. The mean depth of water below the trough was 13 ft. 8½ in., so that in both cases those waves *broke when the depths below their troughs were about twice their own height.* I much regret that I omitted to note the length between the crests. Taking their crests and troughs equi-distant from the mean level of the surface, would give

$$D = 2\,h$$
$$h = \frac{D}{2}$$

when D = depth of water in feet below the mean level, and $h$ = height of wave in feet from hollow to crest.

On the other hand, some of the large waves in Wick Bay during storms were noticed to break when they came into water of the same depth as their height. The height of those waves above the mean level was about two-thirds of their height, the hollow below the mean level was about *one-third.*

It is well also to remember that when the bottom shoals suddenly, the waves are more apt to break than when the shoaling is gradual.

*Height of Waves above the Mean Level.*—The late eminent Dr. Rankine has shown that the mean water-level is not situated half-way between the crest and trough of the sea. He kindly sent me the formulæ for ascertaining the mean level of the sea from the height and length of the wave. His formulæ are *exact* only for water of considerable depth as compared with the length of a wave. For shallower water they are only approximate.

Let L be the length of a wave.
H the height from trough to crest.

Then diameter of rolling circle $= \dfrac{L}{3.1416}$

Radius of orbit of particle $= \dfrac{H}{2}$

And elevation of *middle level* of wave above still water

$$= \frac{3.1416\ H^2}{4\ L} = .7854\ \frac{H^2}{L}$$

Consequently—

$$\text{Crest above still water} = \frac{H}{2} + .7854\ \frac{H^2}{L}$$

$$\text{Trough below still water} = \frac{H}{2} - .7854\ \frac{H^2}{L}$$

# CHAPTER VI.

## DESIGN OF PROFILE, ETC., OF HARBOURS IN DEEP WATER.

Definition of a Breakwater—Best position for a Harbour of Refuge—Comparison of Vertical and Talus Walls—Oscillatory Waves and Waves of Translation—Wind causes Currents—Damage done by Waves in Deep Water—Waves of Translation formed by Unfinished Masonry—Dynamometrical values of forces against Unfinished Masonry—Best mode of Construction for Harbours of Refuge—Level of Conservation of Rubble—Comparison of different Works—Oblique Forces vertically and in azimuth—Ratios of Friction of Stones—Evil of fine Workmanship in Harbour Masonry—Russell on Refuge Harbours—Rubble Breakwaters—Proportions and Costs of different Breakwaters—Different Designs for Refuge Harbours—Available Capacity of Harbours of Refuge and Anchorages.

*Definition of a Breakwater.*—Harbours of refuge are distinguished from tidal harbours mainly by the superior depth of water which they possess, and the larger area which they enclose. The requisites are—shelter during storms, good holding-ground, and easy access for shipping at any time of tide, and in all states of the weather. A breakwater, though a passive, is yet a real agent, having true work to do. During storms many thousand tons of water are elevated and maintained above the sea level, and their motion either stopped or reversed in direction, or destroyed within a given space. This is the work which the breakwater has to do. There are two ways in which the work can be performed. One is by means of a plumb wall to alter the direction of the moving water by causing it to ascend vertically, and then to allow it to descend vertically, by which process the waves are reflected

and sent back seawards. Another mode is to arrest the undulations by a sloping wall of length sufficient to allow the mass of elevated water to fall down upon the slope. If, however, this slope is not long enough to enable the waves to destroy themselves, they will, though reduced in height, pursue their original direction, and pass over the top of the breakwater. In this case the breakwater does not do its full share of work, and little or no shelter is produced.

*Best position for a Harbour of Refuge.*—Having had occasion to go very minutely into this question in reference to the proposed harbour of refuge at Peterhead, on the East Coast of Scotland, and as the points which were involved were of great importance, and affect the whole questions which arise on the general subject; and, in short, the matters discussed must, more or less arise *mutatis mutandis,* in every case, where the proper position for any refuge harbour has to be considered, I shall state the conclusions at which I have arrived on these very important points. It was alleged by the Trustees of Fraserburgh Harbour and their engineer, Mr. Abernethy :—(1) That harbours of refuge for the passing trade are unnecessary; and (2) if any such harbour is to be made, it should be placed at an embayed part of the coast, and not at a salient point. With these views I could not concur, and I was asked by the Trustees of Peterhead Harbour to report to them on the subject.

The Trustees of Fraserburgh Harbour express themselves thus :—" The Memorialists have come to share what they find to be the general opinion of men of maritime experience, that the necessity for a large harbour of refuge, on the East Coast of Scotland, is a thing of the past. Steamers, which have taken the place of sailing vessels, when overtaken by a storm on a lee shore, and unless disabled or scant of fuel

invariably steam to sea, in preference to approaching such a dangerous coast as that of the East Coast of Scotland; and refuge harbours are now more required for sailing vessels of moderate size, and for the protection of the lives and property of the many thousands of fishermen who annually resort to the East Coast."

And Mr. Abernethy, in the report upon which the Trustees found, thus explains his views:—"In determining sites for harbours of refuge regard must be had,—

'*First*, To the number of wrecks occurring on any particular section of coast.

'*Secondly*, To the peculiar causes of these wrecks, viz.—the position of the coast with regard to the on-shore gales.'

"Keeping these points in view, a vessel's liability to be wrecked is when she is abreast a straight line of coast during an on-shore gale, but more particularly if caught within the bight of a bay with projecting headlands to windward; her least liability to wreck being when off a salient point or headland with the coast trending landwards on either side. On the accompanying map I have laid down three lines of embayment (having regard to the fact that coasting vessels generally hug the shore closely in seeking their various ports): *first*, between the port of Aberdeen and Buchanness; *secondly*, between Kinnaird's Head and Lossiemouth; and *thirdly*, from Tarbetness northwards.

"On the first of these sections I remark that Peterhead being situated on a salient point, it is manifest that vessels caught by an on-shore gale to the southward of it, have little chance of escaping shipwreck if they cannot enter a harbour under their lee. The chart shows several wrecks at Peterhead; but these, no doubt, arose chiefly from vessels attempt-

ing, in north-east gales, to round the Buchan Ness with a view of reaching the Moray Firth; in all probability they would not have occurred had there been a safe harbour, under their lee, to run for. Proceeding northwards, if a vessel, after rounding the Buchan Ness, has not sufficient offing to clear Kinnaird or Rattray Head, she must make for one of the Harbours there, or suffer shipwreck. Between Rattray Head and Lossiemouth the same remarks apply, and it will be observed that immediately westward of the latter port the wrecks are numerous, arising from the fact that a reef of rocks, called the "Halliman" and "Covesea Scars," extend a considerable distance seaward. The last line of embayment I have laid down is from Tarbetness northwards, and here it will be observed few wrecks occur, as there is an efficient harbour at Cromarty.

"On the south shore of the Pentland Firth wrecks are numerous, chiefly arising from vessels in northerly gales being unable to weather Duncansby Head.

"The result of these observations, I think, tends to show that, as regards coasters generally, if caught during on-shore gales, which are extremely sudden in their occurrence, they can only be saved by harbours of refuge within limited sections of coast, and that one or two harbours of refuge far apart will not avail them. Means, therefore, should be taken if possible, to provide low-water harbours within the various lines of embayment, which can be done in many cases by the extension and improvement of those in existence."

This much may be conceded on the general question, that if, in the bottom of every bight, there were a safe deep-water harbour, easy of access in on-shore gales, the question of harbours of refuge, in so far as concerns coasters hugging the shore, would be most happily resolved. But in most

cases, and certainly in this, it seems to me that the engineer requires to deal with the normal and not with the exceptional. And the true position for a harbour of refuge is, in my opinion, the very reverse in most respects of that which has been laid down by Mr. Abernethy. Various conditions—statistical, geographical, and local—should be considered in the solution of this question :—

1. *Statistical.*—So far from being necessarily placed in the neighbourhood of local dangers, or as an escape for vessels locally embayed, the harbour of refuge should, in my opinion, be situated as near as possible to the normal route of the greatest possible number of vessels, both large and small. Thus, on the occurrence of a gale, a refuge will be ready, in a position which can be quickly and safely approached by vessels in the ordinary track of shipping ; and therefore, for the same expense of capital and labour as in the Local Harbour Scheme, a much larger proportion both of lives and property will be saved. Vessels, with this haven in view, will be encouraged to hold on their way with a good offing ; or, reaching and using it in time, will avoid the local dangers upon either hand.

2. *Geographical.*—It follows, if the above view be admitted, that the true situation for a harbour of refuge is rather upon a salient than on an embayed part of the line of coast. For (1) the salient part will lie near to the lines of the general passing trade, and (2) vessels seeking such a haven and failing to make it, will not find themselves embayed, but be still well to windward, and have sea-room to bear away for some more distant haven on either hand. There is, indeed, a sense in which a harbour of refuge in the bottom of a bight may be regarded as a source of danger instead of a source of safety. Cardigan Bay, in Wales, for example, is just such a place as

would be selected. But though a harbour in Cardigan Bay might, in certain exceptional cases, do good, that good would be dearly purchased, if the presence of the harbour tempted masters to leave the track of safety and unnecessarily to embay themselves in such a notoriously dangerous locality. It will, I think, be generally admitted that if, from fog or snow showers coming on, a vessel failed to pick up the position of the harbour in the bay, there would be hardly a chance of her escaping shipwreck. A harbour of refuge, on the principle asserted, is either kill or cure, for it offers but one chance to the distressed vessel, which she must seek at the cost of embayment; but a harbour of refuge on a salient part of the coast offers a chance of shelter without necessarily compromising the safety of the ship in case she fails to make it. To conclude, and for reasons too obvious to be mentioned, the harbour of refuge should be as nearly as may be midway between the two nearest *natural* harbours in the track of shipping on that coast.

3. *The Local Conditions* pointing to the proper situation for a harbour of refuge are—(1) the enclosure of the greatest area of sufficiently deep water for the least extent of breakwater to be constructed; (2) the quality of the holding ground in the anchorage thus to be sheltered.

But we are told by the Trustees of Fraserburgh Harbour, that the necessity for a large harbour of refuge, on so dangerous a coast as the East Coast of Scotland, "is a thing of the past." It is not easy to see in what respects the East Coast of Scotland should be, as implied, more dangerous than the East Coast of England, where, as we shall see, harbours of refuge are in great demand. It is no doubt true that there is a heavier sea on the more northerly than on the more southerly coasts of Britain, but there is much to counter-

balance this disadvantage. The south-eastern coasts are notoriously hampered with shoals and sandbanks, a kind of danger which hardly exists at all on the Scotch coasts. But even though it were conceded, for argument's sake, that the Scotch coast is a more dangerous one than the English, it is not easy to see why that should form a reason against providing it with a place of shelter during storms. While it is understood that active movements are now being made for getting harbours of refuge on the English coast at Dover, at Redcar, at Filey, at Sunderland, and at Coquet Island, it can hardly be maintained that such harbours should not be constructed on the Scotch coasts, on the ground that they are not needed. It would surely require strong special reasons indeed to prove that what seems so much wanted in England is not needed at all in Scotland. But still stranger is the further argument of the Memorialists. "Steamers," they say, "which have taken the place of sailing vessels, when overtaken by a storm on a lee shore, and unless disabled or scant of fuel, invariably steam to sea in preference to approaching such a dangerous coast as that of the East Coast of Scotland." This may be so if the harbour of refuge be, according to Mr. Abernethy's ideas, in a bight of the coast line. But it is not so in the case of Peterhead, to which this consideration is intended to refer, and in regard to which it is beside the question. For that port being seated in the true position for a harbour of refuge, the coast retreats both to the north and south of it; it can be approached without coming down upon a lee shore; in south-easterly gales it has under its lee the ample sheltered water of the Moray Firth, and in north-easterly gales there is a sufficient offing, with a leading wind, to make the Firth of Forth; and, to conclude, were there a harbour at Peterhead no steamer would steam

further out to sea than to clear Buchanness, for to do so would be to abandon her direct and natural course, and to incur unnecessary expense, risk, loss of time, and tear and wear.

All who, like myself, have had experience of the shelter afforded at Lerwick and Balta Sound in Shetland; Deer Sound, Stromness, and Long Hope in Orkney; Stornoway, Tobermory, Lamlash, Campbeltown, Loch Ryan, Cromarty, Firth of Forth, and St. Margaret's Hope, know that these natural bays are resorted to in stormy weather by vessels of all sizes, and by both steamers and sailing vessels. It was stated in evidence in the investigations of 1878 and 1882 regarding the Forth Bridge, that in the last-named anchorage alone there are sometimes as many as from three hundred to six hundred vessels of all sizes, including steamers, at anchor at one time during easterly gales, and the same may be said, though not of course to so great an extent, of the other natural harbours I have mentioned. Now, if in these natural harbours of refuge vessels of every description congregate in large numbers, it is impossible to see why they should not equally avail themselves of an artificial deep-water harbour presenting similar advantages.

The suitability of Peterhead has been already amply recognised. It will be enough simply to refer to the evidence collected by the Select Committee on Harbours of Refuge, 1857-58, and to the Reports of the Royal Commission of 1858-59, which unanimously, and after the fullest investigation, recommended the formation of a harbour at that point on the coast; and I shall, therefore, now go on to apply to the particular case of Peterhead the criteria which I have laid down in opposition to the contention of Mr. Abernethy and the Trustees of Fraserburgh Harbour.

1. *Statistical.*—Various lines of commerce lie close past Peterhead. For example, vessels from the Forth ports, viz., Grangemouth, Bo'ness, Alloa, Granton, Leith, Burntisland, etc., also from Dundee, Montrose, and Aberdeen, trading to the White Sea, Greenland, Davis's Straits, the West Indies, the St. Lawrence, and other ports of America, Calcutta, etc., and all vessels bound "north about" must pass Peterhead. Many vessels trading between the Scotch ports and the Baltic with south-west winds frequently sight Buchanness. Peterhead is also a Lloyd's Signal Station for the East Coast of Scotland. The increasing frequency of collisions in the English Channel must lead to an increase in the number of vessels going north about; and possibly Parliament may eventually even enforce the northern route at certain seasons of the year. It is surely apparent how these facts support the anticipated benefits of a harbour of refuge at Peterhead.

2. *Geographical.*—(1) The position of Peterhead on a salient part of the coast, offers precisely what we have seen to be desirable. It is accessible immediately from the high seas. It offers a first chance of shelter to any vessel overtaken by heavy weather, without taking her out of her true course, and without, in the case of her failing to make the harbour, necessarily compromising her second chance to run for either Cromarty, the Orkneys, or the Firth of Forth, as the wind may suit at the time; and (2) Peterhead is situate just about midway between the two nearest natural harbours of refuge in the direct track of shipping,—the Orkneys and the Firth of Forth,—besides being also in easterly storms about seventy miles to windward of Cromarty Bay.

3. *Local.*—(1) The proportion between the deep water enclosed and the length of breakwater necessary. In comparing Peterhead with other competing localities on the same

coast, the advantages of the former, under this head, are very obvious from an inspection of the following Table :—

| | Length of Breakwater to enclose 140 acres having four fathoms and upwards, from Low-water Mark. |
|---|---|
| Peterhead . . . . . | 1000 yards. |
| Wick . . . . . . | 1200 „ |
| Macduff and Banff . . . . | 2400 „ |
| Stonehaven . . . . . | 2500 „ |
| Fraserburgh . . . . . | 2700 „ |
| Aberdeen . . . . . | 2800 „ |
| Arbroath . . . . . | 3300 „ |
| Montrose . . . . . | 4600 „ |

As to the holding ground, Admiral Bedford reported that: "All evidence in support of the good quality of the holding ground I consider fully established by the tests applied in the course of the survey."

(2) There is in the neighbourhood of Peterhead ample and excellent material for the construction of a breakwater.

In accordance with the views stated in the above and former Reports by Messrs. Stevenson, the Committee appointed to investigate the question of the most suitable place for a harbour of refuge on the East Coast of Scotland reported that "No other position on the East Coast of Scotland unites all these advantages, and we have therefore no hesitation in recommending that the harbour to be constructed, upon that coast, should be at Peterhead."

*Comparison of Vertical and Talus Walls for Breakwaters.* —There has been much discussion as to whether piers for harbours of refuge should be *vertical* or *sloping*. Col. Jones, R.E., proceeding on his experience at Kilrush pier, a section of which is given in Plate VII., has specially advocated the superior merits of the vertical wall; and the discussions on

his plan at the Institution of Civil Engineers, and the able protest by the late Sir Howard Douglas, will be found, from their interest and importance, to merit a careful perusal.

The principle asserted in favour of the vertical wall is, that oceanic waves in deep water are purely oscillatory, and exert no impact against vertical barriers, which are therefore the most eligible, as they have only to encounter the hydrostatic pressure due to the height of the reflected billows, which are reflected without breaking.

*Oscillatory Waves and Waves of Translation.*—From the effects of winds and of tide-currents already referred to, and perhaps from other causes, the action of which seems to have been overlooked by the advocates of the upright wall, we have very good reason for believing that any form of barrier, in whatever depth of water it may be placed, must occasionally be subjected to heavy impact. The possibility of waves of translation being generated in the deepest water has been already established in the foregoing chapters, and if the reader has been satisfied, the truth of the following assertions is apparent:—*First,* That oceanic waves break, partially at least, long before they reach the shore, because (as explained even by the advocates of the purely oscillatory character of oceanic undulations) the depth of water is too small to admit of their propagation; *secondly,* That waves in strong tideways break, in deep water, during calm weather—a phenomenon which is apparent to the eye, and familiar to all sailors; *thirdly,* and negatively, That to leeward of those races which produce broken water, and which certainly do not reflect the incoming waves, there is comparatively smooth water both at sea and on the adjoining shore until the strength of the tide is exhausted, and the race has disappeared, after which violent action is again fully manifested on the shore.

It may be argued that these are extreme cases, and that such high tidal velocities are seldom met with. This objection has, no doubt, truth in it; but still the tendency is shown, and, though the velocities may be less in other places, there may yet be a current sufficiently strong to destroy the condition of *stagnation* which the oscillatory theory assumes, to say nothing of the impulsive force of the wind. The breaking of waves at sea, and the existence of races, seem to prove beyond question that at least partially breaking waves are possible in the deepest water.

*Effect of the Wind in causing Currents.*—Wind may also generate currents where there is little tide. It is asserted by Vice-Admiral Zhartmann, in his *Danish Pilot,* that in the Kategat, where the tides have a velocity of 1 to 2 knots, and the common rise is one foot, "the current may sometimes, in boisterous weather, continue to run for three weeks the same way, and even to attain the velocity of 4 knots; and in a furious gale of wind, on the 15th of January 1818, the water rose 5¾ feet above the common water-stand."[1] He also mentions (p. 260) that in the Great Belt the velocity is increased in south-east storms from 1 or 2 knots to 5 knots in the narrows of Hasselö, and that north and west winds produce similar effects in the Sound; and he adds, "Nor is it necessary to this result that the last-named winds should blow home: it is enough that a gale should have swept across the North Sea in that direction for several successive days" (p. 134). If these statements be correct, they certainly prove that the water is driven with force by the wind.

*Damage done by Waves in Deep Water.*—In 1858 the "Hebe" of Wisbeach lost her bulwarks in her passage from Sunderland to Leith, and on examining the crew immedi-

[1] The *Danish Pilot,* by Vice-Admiral Zhartmann. London. 1853, p. 122.

ately after her arrival, the sailors stated that the *weather* bulwarks were the first that were stove in. It will surely be admitted that, in this case, besides the impact due to the velocity of the vessel, the waves must have exerted an impulsive force, and that not due to the action of the wave *after* but before it had broken on the deck. Is it not also probable that even purely oscillatory undulations, after being reflected by a vertical wall, may combine with others of the same kind so as then to become waves of translation, possessing all the elements which endanger the stability of a sea-work?

Dr. Scoresby, in narrating his experience of the storm which he encountered on his voyage to Melbourne in the "Royal Charter" in 1856, gives a graphic account of the breaking of oceanic waves. He says,[1] "No wave could keep pace with the legitimate demands in hydrodynamic law of the wind's terrible vehemence. Waves of 40 feet in height, which satisfy the greatest demands perhaps of any of our North Sea or high northern Atlantic storms, bore no adequate relation to the impetuosity of this hurricane tempest. A sort of surface impetus seemed to be given, forcing the crests of the loftier waves with a velocity so much beyond the motion of the regular undulations, as not only to cast almost every peak and summit into the form of a breaker, but in some cases to give such a degree of magnitude and breadth to the breaking summit—as one mass of white water labouring forward after another, and retarded by the diminished velocity of that before it—that the main surface *behind* some of the mightiest waves would present but one unsubdued and wide-spread breast of foam—a phenomenon I had never seen but in waves breaking over an insulated shelving rock!"

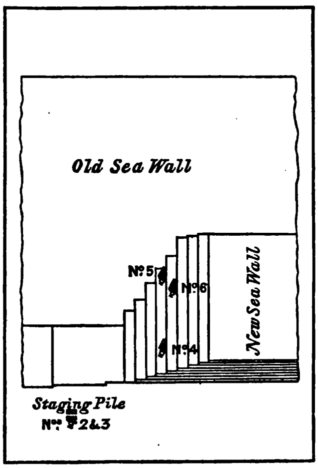
[1] *Life of William Scoresby*, by Dr. Scoresby Jackson. London, 1861, p. 374.

*Waves of Translation formed by the Unfinished Masonry of Deep-water Works.*—But whatever value may be attached to the facts which we have adduced as to the certainty of deep-water waves exerting, in some circumstances, more than the hydrostatic pressure due to their height, there is another consideration, the cogency and relevancy of which can hardly admit of any question. It is a well-known and generally admitted fact, that damage to marine works occurs, in the great majority of instances, during their progress, and not after their completion. Every contractor knows the advantage of having a sea work finished before the storms of winter commence, and it is usual to *close-in* the works with a temporary wall when the autumn draws to an end. Any one may see the obvious propriety of such a course, for it is plain that the stones which are last set have only their own weight to keep them stationary, while in a pier that is finished, the materials are not only bound at both ends, but are kept in their places by the weight of the superjacent masonry. When a storm comes suddenly on during the progress of the works, it at once overturns and removes the outermost stones, and as these expose others, they too, in their turn, speedily disappear, while the mischief is aggravated by the washing out of the still more easily moved backing and hearting. It is manifest, therefore, that this piecemeal destruction will not be confined to the open end of the pier, but will encroach upon the finished work.

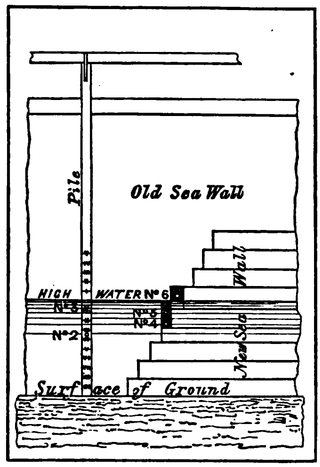
Now, it is equally well known, that in order to preserve the bond in a wall of masonry while in progress, the unfinished end must always present a stepped or serrated outline. It follows, therefore, that even a vertical wall must, during its formation, present constantly to the action of the waves a sloping or at least a stepped face like a talus wall, but which,

unfortunately for its stability, possesses none of the advantages of a finished sloping breakwater. In short, during the most critical period of the history of every vertical wall, the face-work and hearting are exposed at the outer end to the force of *breaking* waves, which not only act upon the materials, but act upon them at the very time when they are in the most defenceless state. These remarks, of course, do not apply to works constructed of concrete.

*Dynamometrical Values of Force against Unfinished Masonry.*—In October 1858, in order to bring these views to the test




Plan.
Fig. 13.




Elevation.
Fig. 14.

of experiment, I fixed small dynamometers on an unfinished wall at the harbour of Dunbar. The works consisted of the formation of a new sea-wall in front of an old one which had become ruinous. Seaward of the new wall the contractor erected piles for supporting a travelling crane. Two dynamometers, marked Nos. 2 and 3 in Figs. 13, 14, were fixed

to the piles, while other three, Nos. 4, 5, 6, were fixed on the unfinished wall. Mr. Russell's law, that waves do not break or become entirely waves of translation until they reach water so shoal as to be no deeper than their own height, appears to hold good for the smaller class of waves; and, therefore, in depths of from 7 to 11 feet 5 inches, being the depths at high water in front of the works, while the trials were made, waves of from 16 inches to 3 feet 9 inches would reach the wall without becoming waves of translation; while waves of from 7 to 10 feet, being those which formed the subject of trial in the first part of the table of experiments given on the next two pages, would in that depth become breaking waves.

On consulting the Table of Observations, it will be seen that the mean force registered on the unfinished courses of the new sea wall, including those imperfect results in which the spring was driven home, was with waves of translation 2.01 times greater than was registered on the pile. This is what might have been expected, for the water in motion would escape more readily past the pile, which presented a very small surface to the moving water, and allowed it to pass freely on both sides. But if we look to the second part of the table we find that the force with the oscillatory or non-breaking waves is 22.45 times greater on the unfinished courses of the masonry than on the pile outside, showing clearly that the broken surface of the unfinished vertical wall had changed their character from oscillatory waves to waves of translation.

OBSERVATIONS made in 1858 at Dunbar Harbour on the Effects of Waves of Translation and of Oscillation against Dynamometers fixed on the unfinished wall, and on isolated piles in front of the wall. The effects are those produced during each tide, the results having been read off at each low water.

| Date of Observation. | Depth at high water in feet. | Waves of Translation. | | | | | | | | | | Height of waves in feet. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. 2. On Pile 7 feet above bottom. | | No. 3. On Pile 9 feet 7 inches above bottom. | | No. 4 On Sea-wall 8 feet above bottom. | | No. 5. On Sea-wall 9 feet 6 inches above bottom. | | No. 6. On Sea-wall 11 feet 2 inches above bottom. | | |
| | | Force in cwts. | Position of Dynamometer. | Force in cwts. | Position of Dynamometer. | Force in cwts. | Position of Dynamometer. | Force in cwts. | Position of Dynamometer. | Force in cwts. | Position of Dynamometer. | |
| 1858. Nov. 5 | $10\frac{1}{4}$ | 5.09 | $3\frac{1}{4}$ | 12.48 | $\frac{1}{2}$ | 6.53 | $2\frac{1}{4}$ | † 45.04 | $\frac{3}{4}$ | 11.81 | 1' dry | 10 |
| 6 | 10 | 6.89 | 3 | 9.70 | $\frac{1}{4}$ | 13.06 | 2 | 15.76 | $\frac{1}{2}$ | 7.09 | 1' 3" dry | 7 |
| 24 | 10 | 8.42 | 3 | † 13.61 | $\frac{1}{4}$ | † 17.61 | 2 | † 23.55 | $\frac{1}{2}$ | 19.27 | 1' 3" dry | 10 |
| 25 | 9 | .94 | 2 | 4.76 | $\frac{3}{4}$ dry | † 17.61 | 1 | † 23.55 | $\frac{1}{2}$ dry | 21.67 | 2' 3" dry | 7 |
| 27 | 8 | † 9.36 | 1 | † 13.61 | 1'9" dry | 3.52 | 0 | † 23.55 | $1\frac{1}{2}$ dry | 6.02 | 3' 3" dry | 7 |
| | | 30.70 | | 54.16 | | 58.33 | | 131.45 | | 65.86 | | |
| | mean | 6.14 | | 10.83 | | 11.67 | | 26.29 | | 17 | | |

## Oscillatory Waves.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. 18 | 9¾ | 0.0 | 2¾ | 0.0 | 0 | 0.0 | 1¾ | 40.53 | ¼ | °—— | 1 6 dry | 3¾ |
| 19 | 10¼ | 0.0 | 3¼ | 0.0 | ½ dry | 6.53 | 2¼ | 22.52 | ¾ | °—— | 1 dry | 1¾ |
| Dec. 3 | 8½ | 1.40 | 1½ | °—— | 1¼ dry | 0.0 | ½ | 14.13 | 1 dry | °—— | 2¾ dry | 2 |
| 4 | 8½ | 0.0 | 1½ | 6.80 | 1¼ dry | 14.08 | ½ | 21.19 | 1 dry | °—— | 2¾ dry | 2 |
| 6 | 10¼ | 0.0 | 3¼ | 0.0 | ½ dry | 4.40 | 2¼ | 8.24 | ¾ dry | °—— | 1 dry | 1½ |
| 7 | 10 | 0.0 | 3 | 0.0 | ¼ dry | 7.40 | 2 | 14.13 | ½ dry | °—— | 1¼ dry | 1½ |
| 8 | 9¾ | 0.0 | 2¾ | 0.0 | 0 dry | 7.40 | 1¾ | 18.84 | ¼ dry | °—— | 1½ dry | 1½ |
| | 9 | 0.0 | 2 | 0.0 | ¾ dry | 0.0 | 1 dry | 21.19 | ½ dry | °—— | 2¼ dry | 1 |
| 11 | 7¾ | 0.0 | ¾ | °—— | 2 dry | 3.52 | ¼ dry | °—— | 1¾ dry | °—— | 3½ dry | 2 |
| 15 | 6 | 0.0 | ½ dry | °—— | 3¼ dry | 2.64 | 1½ dry | °—— | 3 dry | °—— | 4¾ dry | 2½ |
| | | 1.40 | | 6.80 | | 45.97 | | 160.77 | | | | |
| | mean | .14 | | .97 | | 4.59 | | 20.096 | | | | |

*Note.*—The sign † shows that the spring has been driven home, and that the result indicated may not be the maximum.

The sign ° shows that these observations are inapplicable from being above the reach of the waves, and must not be included in calculating the means.

It must be remarked, however, that the dynamometer No. 5 was placed purposely in the angle formed by the junction of the new and old walls, where, as might have been expected, the force was concentrated. This will be perceived on comparing its indications with the others. Although in some parts of every unfinished wall re-entrant angles such as this must exist, where similar concentration of force will take place; yet, even although we exclude its indications from the result, it still appears that the ratio for waves of translation is only 1.46 times greater than that on the log, while with oscillatory waves it is 8.27 times greater.

These experiments prove therefore that *oscillatory waves become waves of translation when they reach the unfinished part of a vertical sea wall, and that they then exert a force nearly* 6 *times greater than if they had remained waves of oscillation* It further appears that purely oscillatory waves do not exert much more than their hydrostatic pressure, under circumstances similar to those affecting the Dunbar experiments; but had there been a storm of wind, those waves would no doubt have ceased to be purely oscillatory, even although the water had been very deep.

*Best Mode of Construction for a Harbour of Refuge.*—With reference to the best mode of construction for a harbour of refuge in an exposed situation, there will always be considerable differences of opinion among members of the profession. I shall simply state the form of construction which, on the whole, I consider to be best in situations where the place is fully exposed to the heaviest class of waves.

A very obvious and very important point regarding the stability of such a structure as a breakwater has reference to the depth below low water at which the waves cease to exert any considerable impact upon the materials on which the superstructure rests. It was found at Wick that the very anomalous waves which assailed that work did not disturb

any of the rubble base at a lower depth than 18 feet under low water. I am therefore of opinion that a level of from 18 to 20 feet below low water may be safely assumed as that of practical stability. I conceive that the safest and most economic profile of construction is, as shown in Fig. 15, a mass consisting of large rubble extending to within 20 feet of low water; when the base has been brought up to this level, blocks of concrete, weighing from 100 to 200 tons, should be deposited on the top and outer or seaward surface of the rubble base, till they come above low-water level. Betwixt the spaces, at the top of these blocks, bags of concrete

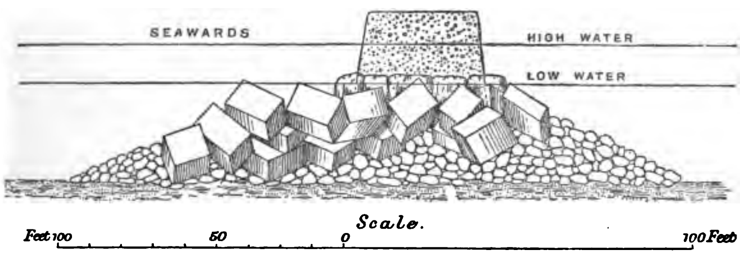



Fig. 15.

should be placed so as to form a level platform above low-water level. Upon this a solid mass of concrete *in situ*, should extend from end to end of the breakwater, which should not be less than 10 feet above high water, and about 45 feet in breadth. A structure designed on these principles will, I think, be found able to resist the force of the sea in any situation, provided the sea slope be of sufficient extent. The design shown in Fig. 15, is that proposed by Messrs. Stevenson for the harbour of refuge at Peterhead.

*Level of Conservation of Rubble.*—If we further keep in view that any settlement of the foundation is far more perilous to a vertical than to a sloping wall, there

seems good ground for believing that the ordinary method of forming the low-water parts of deep harbours of large masses of rubble stone or of concrete blocks, is, in most circumstances, the best and cheapest kind of construction when a vertical wall is to be adopted. Loose rubble or blocks of concrete, after being acted upon by the waves, are less liable to sink, or to be underwashed, than when a vertical wall is founded upon a soft bottom. Loose concrete blocks above low water form an excellent protection to the upright wall. Two precautions should, however, be kept in view—*First*, the wall should be founded at a sufficiently low level to prevent underwashing. A depth of from 12 to 15 feet under low water was pointed out by the late Mr. J. M. Rendel as the level below which the waves did little or no damage to *pierres perdues*. Sir John Rennie indeed considered that there was little or no effect at a fathom and a half.[1] No works executed at an earlier date than those at Wick had been founded at a lower level than 12 feet; but at Pulteneytown, where the rubble is more exposed than at any other harbour, Messrs. Stevenson, as already stated, considered it advisable to found the wall 18 feet below low water, and the rubble was moved down to 18, and at Alderney to 20, feet below low water. *Secondly*, in all cases where the structure is to act simply as a breakwater, and not as a pier, there should be no parapet, the want of which relieves the foundation, as was observed by Mr. D. Stevenson at a harbour work where a breach had been made. At one part, where the wall remained entire, and the sea was opposed by the parapet, the sea fell heavily on the foundations; but at the breach, where the parapet was wanting, the waves played gently over the work without any perceptible reaction against the foundation courses.

[1] *Min. Civ. Eng.*, vol. vi. p. 122.

Mr. Murray also approves of there being no parapet, and proposes that the roadway of breakwaters should be 10 feet above high water. When pitched slopes are adopted, great benefit will be found to accrue from leaving a wide foreshore at the bottom or toe of the slope. Much, however, depends on local peculiarities in selecting the best design for any work; and the nature of the bottom is in all cases important. Where the bottom is soft a high vertical wall should not be attempted.

*Comparison of different Works.*—In making these remarks, I must not be understood as condemning the adoption of vertical walls without a rubble base, in cases where the foundation is good. All that is asserted is the opinion that partial waves of translation do exist in deep water, and therefore that harbours of refuge will prove failures unless they are built of sufficient strength to resist the impact of such waves. The Cherbourg breakwater (Plate VII.) has been often referred to as a successful instance of the application of a vertical wall, and has been contrasted with the Plymouth breakwater, which has a long slope. But this appeal is quite fallacious, as the Cherbourg breakwater is of a composite character, consisting of a mass of rubble sloping at the rate of 7 horizontal to 1 perpendicular, surmounted by a plumb wall; so that whatever merit may be supposed to belong to the vertical profile is entirely nullified by the long slope in front, on which the waves break before they reach the vertical barrier. Moreover, the heaviest waves at Cherbourg come from the N.W., and do not assail the breakwater at right angles to its direction, but come more nearly *end on* to the work, so as to a great extent to run easily along the outer wall. The N.W. waves are propagated from the Atlantic, while those which prove most trying to the work come from the N., in which

direction the extent of exposure is only about 60 miles. These facts were obtained during a visit to Cherbourg, undertaken for the special purpose of ascertaining the physical characteristics of the place. Any attempt to establish a parallelism between Plymouth, which faces the Atlantic directly, and Cherbourg, which is comparatively land-locked, cannot, therefore, stand the test of a careful inquiry.

Other comparisons may be referred to which have been advanced on equally untenable grounds. Thus, the old pier of Dunleary, which is vertical, and has stood well, has been compared with the talus walls of Kingstown Harbour, which now protect Dunleary, and which have often received much damage. The all-important element of the *depth of water* in front has in this comparison been entirely overlooked; for at Kingstown there is a depth of 27 feet, while Dunleary is all but dry at low water.

*Oblique Force in the Vertical Plane.*—An important advantage of the sloping wall is the small resistance which it offers to the impinging wave, but it should also be borne in mind that the weight resting on the face-stones in a talus wall is decreased in proportion to the sine of the angle of the slope. If we suppose the waves which assail a sloping wall to act in the horizontal plane, the component of their impulsive force at right angles to the surface of the talus will be proportional to the *sine* of the angle of inclination to the plane, while the effective force, estimated in the horizontal plane, will be proportional to the *square of the sine* of the angle of inclination. But if we assume the motion of the impinging particles to be horizontal, the number of them which will be intercepted by the sloping surface will be also reduced in the ratio of the sine of the angle of inclination, or of the inclination of the wall to the vertical. Hence the tendency of the waves to

produce horizontal displacement, on the assumption that the direction of the impinging particles is horizontal, will be proportional to the *cube of the sine of the angle of elevation of the wall.*

*Formula for Oblique Force vertically and in Azimuth.*—If it further happen that, owing to the relative direction of the pier and of the waves, there is an oblique action in azimuth as well as in the vertical plane, there will be another similar reduction in the ratio of the squares or cubes of the angle of incidence, according as the component of the force is reckoned at right angles to the surface of the pier, or in the direction of the waves.

Let $f$ = force of the wave on unit of surface of wall for perpendicular incidence;

$f'$ = force on unit of surface at vertical incidence $\phi$, and azimuthal incidence $\psi$;

then $$f' \propto f\,(\sin\phi \sin\psi)^3.$$

The above expression may perhaps appear to assign too great a reduction to the oblique action, because the motion of many of the particles is not horizontal, and the upward force acting over the area of the lying beds of the stones is perhaps more to be dreaded when the works are in progress than the horizontal force against the outer vertical faces. Yet it must be observed that the experience at Wick breakwater already referred to points to a different conclusion.

*Ratios of Friction for different kinds of Masonry.*—More extended experiments than have yet been made are desirable to determine the *constant* for the friction of rough blocks over each other. Mr. George Rennie found that $\frac{8}{10}$ths of the weight were required to drag a block of stone over the roughly-dressed floor of a quarry, and that the voussoirs of the London Bridge began to glide over each other at a slope

of from 33° to 34°.[1] I made a few experiments on the friction of small, polished, ashlar blocks of freestone, and the mean gave $\frac{5}{10}$ths of the whole weight moved, as the coefficient of friction of such stones over a similarly polished freestone block.

The power required to *extract* a polished freestone block out of its place in a column consisting of different numbers of blocks was also tried. The coefficient of friction in extracting any of the blocks from the column was 1.083, or about *twice* the amount for moving the whole mass (including the stone extracted).

As the blocks in a sea-work are very often submerged, it appeared desirable to ascertain the friction in water as well as in air, and the following table shows the results, as also the coefficients for stones in different styles of dressing.

| Kinds of Dressing and of Materials. | Angles at which blocks began to move. | | Coefficients of Friction for Water. | Coefficients of Friction for Air. |
|---|---|---|---|---|
| | In Water. | In Air. | | |
| Polished freestone on polished freestone | 28° | 28° | .53 | .53 |
| Longitudinal axing on cross broaching[2] | ... | $37\frac{1}{2}$° | | .77 |
| Cross axing on cross broaching . | ... | $38\frac{1}{4}$° | | .79 |
| Closely axed greenstone on scabbled freestone . . . . . . | 39° | 35° | .81 | .70 |
| Longitudinal broaching on pick-dressing | ... | $39\frac{1}{4}$° | | .82 |
| Closely axed greenstone on scabbled freestone . . . . . . | ... | 40° | | .84 |
| Cross close axing on pick-dressing . | $41\frac{1}{3}$° | $40\frac{1}{8}$° | .88 | .84 |
| Longitudinal broaching on longitudinal broaching . . . . . | 41° | $41\frac{1}{3}$° | .87 | .88 |
| Closely pick-dressed freestone on closely pick-dressed freestone . . | 51° | 43° | 1.23 | .94 |

[1] *Phil. Trans.* 1829, p. 168.

[2] *Broaching* is a style of work peculiar to Scotland, and consists of a number of narrow parallel ridges running close to each other. They are made with a sharp-pointed tool, and extend over the whole of the face-work between the *drafts*.

The blocks which were used in these experiments were of too small sizes to give anything more than a rough comparative valuation for air and water, but some stones of about a ton in weight were dressed for me in different styles of workmanship, at the sight of Mr. Robert Kinnear, Inspector of Works, when the following results were obtained :—

| Kind of Dressing | Angles at which Stones began to move in Air. | Coefficients of Friction in Air. |
|---|---|---|
| Droving on droving, waves parallel to line of slip | 33° 8′ | .65 |
| Broaching on broaching, with strips or ridges running parallel to the line of slip . . . | 34° 3′ | .68 |
| Droving on droving, waves cross to line of slip . | 35° 57′ | .73 |
| Broaching on broaching, with strips or ridges lying crossways to the direction of slip . . . | 36° 6′ | .73 |
| Rough pick-dressing on rough pick-dressing . | 38° 11′ | .79 |

*Evil of Fine Workmanship in Harbour Masonry.*—These tables are given not as determining the different coefficients exactly, but as establishing the fact that the friction in water is much the same as in air; and as showing the impropriety of expending labour in finely dressing the materials for harbour masonry. By polishing the beds of masonry it was found that the power of resistance was reduced by about *one-fourth;* or, in other words, roughly dressed materials of *three-fourths* of the weight of polished materials will be equally safe, while they are also more economical, both as to the cost of the stone and of the workmanship in dressing.

*Mr. Russell's Remarks on Harbours of Refuge.*—I have already referred to the importance of Mr. Scott Russell's experimental inquiries, and I cannot do better than conclude the remarks on this subject by a quotation from his observations during a discussion at the Institution of Civil En-

gineers, the value of which will, no doubt, be regarded by the reader a sufficient excuse for its length.

"In sea-works there were practically two classes of waves to deal with, of such different, if not opposite, natures, that what was beneficial in the one case was often useless in the other. . . . In deep water there were not only the oscillating surface-waves to be encountered, but also those which he had termed waves of translation, forming what were called rollers at the Cape of Good Hope, and when on a smaller scale, known as ground-swell. These were a much more troublesome class of waves; it was mainly with them that the engineer had to deal, in places open to the Atlantic; and after a storm of some duration at sea they became the deadliest enemies, in the cases of deep water, against which breakwaters for harbours of refuge had to contend. These rollers or ground-swell did not merely oscillate up and down, but backwards and forwards; and they could not be eluded, or turned back, by giving to the wall a particular curve suited to the form of a cycloidal oscillation.

"These great waves of translation constituted a vast mass of solid water, moving in one direction with great velocity, and this action was nearly as powerful at a great depth as at the surface. They resembled the tidal bore of the Hooghly, of the Severn, or of the Dee; they formed a high and deep wall of water of great weight, moving horizontally with great force, and causing all floating bodies they met with to travel with them with great velocity in the same direction. As he had before mentioned, they could not be eluded or diverted, they must be stopped; and therein consisted the difficulty. The only certain way of effecting it was to oppose to these waves a mass of matter so much heavier than themselves that they could not move it. By so doing, the waves were com-

pelled either to roll over the obstacle, in which case they would create a new wave inside, or they must be made to break on themselves backwards, which required enormous power; or they must be completely reflected, which, perhaps, required the greatest force of all.

"To reflect or send back the roller was the most effectual plan. For this purpose nothing more was necessary than a deep perpendicular face of perfect masonry, and so long as it stood firm it was faultless, and the water inside was smooth as in a mill-pond; for the reflection really converted the whole effect of the roller on itself into a simple pressure of water. When such a wave was reflected on a perpendicular wall it merely produced a hydraulic pressure equal to that due to little more than double its own height. A roller 20 feet in height would produce a pressure of about a ton per foot, and it would be reflected by a vertical wall of moderate dimensions. He had, therefore, no hesitation in saying that, cost apart, a wall of vertical masonry was the best while it lasted. The primary cost of erecting a vertical wall of perfect materials was, in most cases, so great as to put it out of the question, setting aside the important point of durability, which was also cost in a serious form. A vertical wall of masonry had, however, this great disadvantage: if the sea found out a weak place it would enlarge it much more rapidly than in an inclined wall. He had seen a stone of small size show symptoms of crumbling at the beginning of winter, and in one week the little hole of single defective stone was converted into a circular breach nearly 30 feet in diameter. An inclined wall, he had ascertained, would reflect a roller or deep wave nearly as well as a vertical wall, down to an inclination of 45°. This observation was of value, because at 45° large blocks, judiciously placed, would not move out of

position, even although a considerable breach was made in the wall near them. He had carefully watched the action of the sea when approaching this slope, and his opinion was favourable to the trial of a wall of heavy rubble blocks fairly laid, so as to form a tolerably even face or slope of 45°, when the nature of the materials and the local circumstances would permit.

"When any approximative attempt at reflection of the wave, by walls not too remote from the vertical, had to be abandoned, recourse must generally be had to breaking the wave. This was a formidable thing to attempt on a deep-sea roller, and it could only be done by opposing mass to mass. For this purpose he had ventured to recommend that the forefoot of the breakwater should be rounded off, and that the shape of the breakwater should be convex. The intention of this was, to cause the front wave to begin breaking at the earliest moment, to make the breaking last as long as possible, and thus to render the diminution of its momentum as complete as was practicable. In breaking a wave, it was very important that it should be made to break on the water and not on the stones; and the convexities given to the foreshore accomplished this object, by causing the waves to begin breaking as far out as possible in deep water. The form for breaking a deep roller should be entirely distinct from that used for meeting a superficial oscillating wave; the one should be concave, the other convex. The Digue, or breakwater of Cherbourg (Plate VII.), showed an approximation to this form. A breakwater, to succeed in breaking the long waves of translation, rolling in from deep water after a storm, should have a long convex slope.

"The practical construction of breakwaters was, however, scarcely confined either to resisting deep-sea rollers, or waves

of translation, or to procuring the means of stopping the progress of common sea waves, or mere surface oscillation; it usually combined both of these objects. It might, therefore, be considered as the general problem of a breakwater—first, to stop out the great wave of translation, and secondly, to still the oscillating surface-wave. A vertical wall effected both these conditions, and so also did a convex sea-slope with a vertical pier. But the best plan of all was, first to carry up a convex sea-slope of rubble to near the surface of the water, and thus break the force of the heavy ground-swell, that would sweep ships from their anchors and lay them high and dry on a lee shore. This would allow the wave to break to pieces on itself, and to expend its force in raising so much water as represented its momentum to a height above its former place sufficient to exhaust its power; in other words, to expend its power on water. Secondly, to carry up from the top of the rubble slope a wall slightly inclined, to reflect the waves of oscillation near the surface, which could do no harm if quietly resisted and sent back. This plan seemed to be that which had been found to answer best in practice. He further considered, that making a step backwards in the upper work of a breakwater was of great value in preventing the tops of the waves from going over. He had carefully watched the effect at Marseilles, and his observation had confirmed the opinion he expressed in favour of it in 1847.

"These views of the nature of the forces to be resisted in breakwaters, and the methods of dealing with them, showed the inefficiency of what were called floating breakwaters. Large floating masses would certainly intercept oscillating waves of a small depth, and in moderate weather they would often still the water. The lee side of the "Great Eastern," when lying at Holyhead, afforded excellent anchorage for

small vessels in light breezes. But when the great roller, the one great wave of translation, came, the anchors snapped at once, showing the danger which would have been incurred had she been moored broadside to the roller, instead of offering to it the small resistance of her fine bow. No known force could effectively secure a large floating breakwater broadside-on to a heavy ground-swell. It would move horizontally with the wave of translation, which would propagate itself along the bottom, just the same as if the breakwater was not there."

*Examples of Rubble Breakwaters.*—According to Sir John Rennie (*Account of Plymouth Breakwater*), rubble breakwaters, with slopes formed at the angle of repose, were adopted by the Greeks in the moles of Tyre and Carthage, and by the Romans at Athens and Halicarnassus. The same design was also followed at Venice, Genoa, Rochelle, Barcelona, and other places. In this kingdom the first example on a large scale which we find is at Howth. Kingstown and the noble breakwater at Plymouth (Plate VII.), as regards the portion under low water, were afterwards carried out on the same principle, chiefly under the directions of the late Mr. Rennie. The great national harbours of refuge at Holyhead and Portland (Plate VIII.), formerly under the late Mr. Rendel, and latterly under Sir John Hawkshaw and Sir John Coode, are on a similar principle ; while those of Messrs. Walker and Burgess, at Alderney, and of Mr. Messent, at the Tyne, are either nearly vertical or composite (Plate VIII.).

*Proportions of Breakwaters.*—The following table of the principal proportions of some of the most important breakwaters may be found useful as a guide in designing works of a similar kind :—

## TABLE OF PROPORTIONS OF DIFFERENT BREAKWATERS.

| Name. | Kind of Work. | General Slope of Outer Face. From Bottom to near Low Water. | General Slope of Outer Face. Near Low Water. | General Slope of Outer Face. Up to High Water. | General Slope of Outer Face. Above High Water. | Inner Slopes. Above High Water. | Inner Slopes. Below Low Water. | Inner Slopes. Top above High Water. | Level of top of loose rubble below low water. | Level of foundations of wall below low water. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | SLOPING BREAKWATERS. | | | | | | |
| Plymouth. | Pitched Slopes above L. W., loose rubble below. | $1\frac{3}{4}$ to 1 | 4 to 1 | 5 to 1 | 5 to 1 | 2 to 1 | 2 to 1 | 3 feet. | 0 | 0 |
| Portrush. | Slopes of loose rubble. | $1\frac{3}{4}$ to 1 | 6 to 1 | 3 to 1 | $1\frac{1}{2}$ to 1 | $1\frac{1}{2}$ to 1 | 1 to 1 | 16 feet. | 0 | |
| Kingstown. | Pitched slopes of rubble. | $1\frac{3}{4}$ to 1 | 5 to 1 | 5 to 1 | 5 to 1 | $\frac{1}{3}$ to 1 | $\frac{1}{3}$ to 1 | 15 feet. | 0 | 0 |
| | | | | COMPOSITE BREAKWATERS. | | | | | | |
| Portland. | Slopes of loose rubble, with plumb wall founded at low water. | $1\frac{1}{4}$ to 1 | 5 to 1 | $4\frac{1}{2}$ to 1 | Plumb wall. | Plumb wall. | 1 to 1 | 25 feet. | 0 | |
| Holyhead. | Slopes of loose rubble, with plumb wall founded at low water. | 2 to 1 | 5 to 1 | 12 to 1 | | | $1\frac{1}{4}$ to 1 | 25 feet. | | 0 |
| Cherbourg. | Slopes of loose rubble, with plumb wall founded at low water. | 2 to 1 | 7 to 1 | Plumb wall. | Plumb wall. | $\frac{1}{6}$ to 1 | 1 to 1 | 15 feet. | 0 | 0 |
| Alderney. | Slopes of loose rubble, with wall above. | 2 to 1 | 5 to 1 | Wall $\frac{1}{2}$ to 1 | $\frac{1}{2}$ to 1, & plumb | Wall $\frac{1}{3}$ to 1 | $1\frac{1}{4}$ to 1 | 25 feet. | 0 | 12 |
| Cette. | Do. | $1\frac{1}{2}$ to 1, & 6 to 1 | $3\frac{1}{2}$ to 1 | Wall | Wall | | $1\frac{1}{2}$ to 1 | $12\frac{1}{2}$ feet. | | |
| Pulteneytown. | Do. | From bottom to 15 ft. below low water. 1 to 1, & 7 to 1 | Wall $\frac{1}{6}$ to 1 | $\frac{1}{6}$ to 1 | $\frac{1}{6}$ to 1 | $\frac{1}{8}$ to 1 | $\frac{1}{8}$ to 1 | 6 feet, and 21 feet. | 15 | 18 |
| | | | | VERTICAL BREAKWATERS. | | | | | | |
| Dover. | Built solid with concrete blocks, faced with granite, and has a solid concrete top. | $\frac{1}{4}$ to 1 | $\frac{1}{4}$ to 1 | $\frac{1}{4}$ to 1 | $\frac{1}{4}$ to 1, & cavetto | $\frac{1}{4}$ to 1 | $\frac{1}{4}$ to 1 | 23 feet. | | 45 |
| Aberdeen. | Concrete, in blocks below L. W., and solid concrete above. | $\frac{1}{8}$ to 1 | $\frac{1}{8}$ to 1 | $\frac{1}{8}$ to 1 | $\frac{1}{8}$ to 1 | $\frac{1}{8}$ to 1 | $\frac{1}{8}$ to 1 | 10 feet. | | 20 |

*Relative economic Values of Different designs for Breakwaters.*—I have collected the following costs of different breakwaters from the Minutes of the Institution of Civil Engineers, and other sources.

| Name of Breakwater. | Depth of water in fathoms at low water. | Cost per lin. yard. | Remarks. |
|---|---|---|---|
| Joliette, Marseilles | 5 to 6 | £225 | |
| Algiers . . . . | 6 to $10\frac{1}{2}$ | 366 | No rubble, all large beton blocks. |
| Holyhead . . . | 3 to 9 | 489 | |
| Marseilles (new) . | 5 to 9 | 328 | |
| Portland . . . | 8 to 10 | 348 to 360 | Convict labour. |
| Alderney . . . | 3 to 22 | 705 | |
| Dover . . . . | 1 to 7 | 1080 | |
| Plymouth . . . | 6.6 to 7.5 | 600 | |

Although some of these prices have given rise to lengthened discussions as to the comparative economic advantages of the various designs, I fear that the results have not been of much value, on account of the different degrees of exposure and of depth of water at the various places. The economic values may perhaps be arrived at in a more satisfactory manner, although still but only very approximately, thus :—When $x$ = the price per foot of depth, $p$ = the price per lineal foot, and $d$ = the depth in feet at high water.

$$x = \frac{p}{d}$$

The results calculated in this manner are arranged in order of their costs in the following Table :—

| Name of Harbour. | Average depth in feet at high water. | $\frac{p}{d}$ in £ and dec. |
|---|---|---|
| Portland . . . . | 67 | £1.76 |
| Joliette . . . . | 35 | 2.14 |
| Algiers . . . . | 50 | 2.44 |
| Marseilles (new) . . | 43 | 2.53 |
| Alderney . . . . | 80 | 2.93 |
| Holyhead . . . | 54 | 3.01 |
| Plymouth . . . | 57 | 5.1 |
| Dover . . . . | 40 | 9. |

From this view of the subject the plumb pier of Dover appears to be by far the most costly.

*Different Projects for constructing Harbours of Refuge.*—After the general opinions that have already been expressed, and in anticipation of what follows, regarding the action of the waves, and the choice and relative durability of different materials, it is not necessary to describe the projects for constructing harbour works which have from time to time been brought forward by amateur engineers. So far as my experience has gone, I incline a good deal to the opinion that there is no *royal road* to harbour-building, though I should be far from discountenancing any attempts at improvement, from whatever quarter they may come; and here I would remark, what will be afterwards referred to, that the hydraulic properties of Portland cement go far to meet the difficulties arising from want of continuity in marine structures of masonry.

The same remarks as to novel designs do not of course apply to others made by those who are professionally acquainted with the subject; but I have no wish to sit in judgment upon the merits of any *individual* design, whether made by engineers or others, as such a course might lead me to express unfavourable opinions on some points. I will there-

fore only give a very brief description of some of these, leaving the reader to form his own judgment as to their relative merits.

*Vertical Wave-Screens.*—Isolated piles of timber or iron, placed at certain distances apart, have been proposed as breakwaters by the late Captain Vetch, R.E., and Captain Calver, R.N.

Captain Calver proposes to form a breakwater, or, as he terms it, a wave-screen, consisting of a row of vertical piles driven into the bottom at certain distances apart. They are to be united horizontally by iron runners, and supported laterally by sloping struts having large iron shoes attached at their lower ends for entering and abutting against the bottom, while their upper ends are proposed to be connected with the main upright piles by swivel joints, to admit of their being placed at any angle. The shorter of the struts is to abut upon the main upright a little above the level of low-water, while the longer one is to abut upon the main pile at a corresponding height above high-water. A short chain extends to the longer strut from near the place where the lower strut joins the main upright. At the top the main piles are connected together by a narrow continuous gangway with handrail outside. The piles are proposed to consist either of timber or of wrought iron. The screen is intended for a low-water depth of 36 feet, a tidal rise of 15 feet, and a maximum wave of 15 feet. The gangway is to be elevated about 14 feet above the undisturbed high-water level. The shoes of the struts are to be of a peculiar shape, so as to present a vertical flat surface to the soil in which they are buried. These struts are not to be driven into the soil, but are to be "buried beneath the surface by the tidal current." Captain Calver anticipates that the strength of this framing

will be greatly more than sufficient to withstand "any force that could possibly be brought against it." For a full description of the structure and of the merits claimed for it, the reader is referred to Captain Calver's *Wave-Screen*, published at London in 1858, which contains much interesting information relating to the subject of harbours.

*Horizontal Wave-Screens.*—Mr. Brunlees recommends a breakwater and pier of cast and wrought iron. The piles are intended to be placed zigzag, at an angle of 90°, with the view of increasing the strength of resistance. The piles are to be sunk, where the soil is sandy, by the hydraulic process, which was successfully used by him for sinking the Morecambe Bay viaducts. The spaces between each pile are to have horizontal louvre boards attached, and, as the spaces are short, the louvre boards are intended to be of cast-iron. The space between low water and the bottom is left comparatively open, with the view of avoiding interference with the run of the tides.

Mr. M. Scott has suggested a combination of horizontal wave-screens with a rubble base; the construction and advantages which he claims for it are thus described by him:—[1]

"In the case of deep water, and where stone is to be readily obtained, a bank of rubble might be deposited, rising to within, say 15 feet or more of low-water mark, the height of the bank varying with the circumstances of the locality. Upon this bank it is proposed to build a face wall up to low-water mark, and behind this wall long counterforts, the upper surface of which would rise from low water at an inclination of about 2 to 1, and extend back for a distance dependent upon the amount of slope rendered necessary by the magnitude of the waves. These counterforts would be placed at

[1] *Minutes of Institute of Civil Engineers*, 1860, p. 649.

sufficient intervals, say of 20 feet, so as to be conveniently spanned by iron girders, and the whole of the sloping surface would be converted into a sort of gridiron, by girders laid from pier to pier, the upper flanges being about 1 foot wide, and the girders laid at intervals of about 18 inches.

"Supposing such a breakwater to be erected and exposed to a heavy sea, if the waves are not breaking the water would be projected up the slope, and would drop through the spaces between the girders; and if the waves are breaking they will rush up the slope as a confused mass of water, dropping through on their passage. But, although it is anticipated that the great bulk of the water would pass through the grating and not return to the foot of the slope, the operation would be gradual and be diffused over a considerable surface, so that a wave would not be reproduced inside. The only effect would be a stream of water into the harbour, and in this particular the proposed form differs in principle from all vertical screens or gratings, which, by permitting the waves to pass through at the same instant of time, have not the effect of destroying the undulation. The breakwater should, if possible, be placed at an angle with the direction of the greatest sea, so that a wave should not only run up the slope, but along it, diffusing itself in this manner over a much larger area."

*Timber Breakwaters in Deep Water.*—Mr. Abernethy and Mr. M. Scott have proposed to apply to harbours of refuge in deep water the timber-box principle, which has been long in use for tidal harbours, to which reference will afterwards be made, and of which drawings will be found in Plates IX. and X. Mr. Scott suggests that the structure may be formed by simply resting frames of timber upon the bottom, without having any piles driven into the ground, a plan which has

been carried into execution in shallow water at Blyth (Plate IX.)

Mr. Scott has also described a method of making the bottom of the structure flexible, so as to admit of its resting fairly on the ground. The floor beams are for this purpose made in pieces of small length, being placed single and double alternately, and connected together with bolts so as to adapt themselves approximately to the irregularities of the bottom on which they are to rest.

*Available Capacity of Harbours of Refuge.*—Mr. Mather remarks[1] that smaller vessels require 40 fathoms, while ships of 200, 300, and 400 tons require 60 to 80 fathoms; and giving room to swing clear of anchors, 150 vessels would fill up 470 acres of 18 feet and upwards, and 325 of 12 feet and upwards.

This would give as a mean *about* .5 *vessel per acre.*

Minard allows for the mooring of man-of-war vessels 2 cables, and for large merchant vessels somewhat less than a half.

Captain Calver allows .33 *vessel* per acre for a small sheltered harbour of refuge.

*Available Capacity of Anchorages and Natural Bays.*—At Cardiff Flats there were at one time 224 vessels beached as close to each other as they could well be, in an exposed situation, and occupying a space of 560 acres, at the rate of .4 *vessel per acre.*

[1] *Ships and Gales*, by J. Mather. London, 1858.

# CHAPTER VII.

## DESIGN OF PROFILE, ETC., FOR TIDAL HARBOURS.

Weight better than Strength—Movement of Lighthouse Masonry—Effect of Configuration of Rocks on breaking Waves—Forces outside of Masonry—Horizontal and Vertical Forces—Cavettos and String Courses—Rise of Spray—Vertical Force—Back Draught—Forces within Masonry—Piers of insufficient Width—Rarefaction of Air—Rock Foundation—Durability and Strength of Rocks—Wasting of Rock Foundations—Profile with large Materials—Profile with small Materials—Properties of Rocks—Buildings on soft or sandy Foundations—Profile of Conservancy—Walls of Horizontal and Vertical Profile—Clay Foundation—Application of Principles—Exposed Sandy Coasts.

HAVING considered the few facts which have been ascertained regarding the action of the waves in the open ocean, I shall now direct the reader's attention to their effects in shallow water. The undulations in deep water are chiefly *whole waves,* and regarded by many as being purely oscillatory, while those in shoal water are breaking waves, and therefore regarded by all as waves of translation. We have hitherto been considering outer breakwaters erected in deep water, and which are constantly exposed to the waves; we now turn to piers and sea-walls which are placed within the range of the breaking surf, and which are exposed to its force for a limited period only, being sometimes left nearly or altogether dry by the receding tide.

*Stability better attained by Weight than by Strength of Materials.*—In dealing, then, with waves which are by all

admitted to exert a true percussive force, the question arises as to how this force may be best resisted—whether by opposing to it *dead weight,* or a comparatively light structure, the stability of which is dependent on bolts or other strong fixtures connecting it with the bottom. I cannot do better than quote the following remarks on this subject by the late Mr. Alan Stevenson, which were made with reference to the stability of lighthouse towers, but which apply more or less to every work which is placed within reach of the waves :—

"A primary inquiry as to towers in an exposed situation, is the question whether their stability should depend upon their *strength* or their *weight;* or, in other words, on their *cohesion* or their *inertia?* In preferring weight to strength we more closely follow the course pointed out by the analogy of nature ; and this must not be regarded as a mere notional advantage, for the more close the analogy between nature and our works, the less difficulty we shall experience in passing from nature to art, and the more directly will our observations on natural phenomena bear upon the artificial project. If, for example, we make a series of observations on the force of the sea as exerted on masses of rock, and endeavour to draw from these observations some conclusions as to the amount and direction of that force as exhibited by the masses of rock, which resist it successfully, and the forms which these masses assume, we shall pass naturally to the determination of the mass and form of a building which may be capable of opposing similar forces, because we conclude with some reason that the mass and form of the natural rock are exponents of the amount and direction of the forces they have so long continued to resist. It will readily be perceived that we are in a very different and less advantageous position, when we attempt, from such observations of natural phenomena in which *weight* is

solely concerned, to deduce the *strength* of an artificial fabric capable of resisting the same forces, for we must at once pass from one category to another and endeavour to determine the strength of a comparatively light object which shall be able to sustain the same shock which we know by direct experience may be resisted by a given weight. Another very obvious reason why we should prefer mass and weight to strength as a source of stability is, that the effect of mere inertia is constant and unchangeable in its nature, while the strength which results even from the most judiciously disposed and well executed fixtures of a comparatively light fabric is constantly subject to be impaired by the loosening of such fixtures, occasioned by the almost incessant tremor to which structures of this kind must be subject from the beating of the waves. Mass, therefore, seems to be a source of stability, the effect of which is at once apprehended by the mind as more in harmony with the conservative principles of nature, and unquestionably less liable to be deteriorated than the strength which depends upon the careful proportion and adjustment of parts."[1]

*Movement of Lighthouse Masonry.*—Although there is a great difference between the action of the sea on the masonry of harbours and of lighthouses on exposed rocks, yet in both cases we have the same agent to deal with, and we know that if a given diameter of tower prove insufficient for the perfectly fitted masonry of a lighthouse, the breadth corresponding to that diameter must *a fortiori* be insufficient for a harbour with a similar exposure. In briefly adverting to some peculiarities of one or two of these structures, we shall further learn how difficult it is to arrive at a correct appreciation of the exposure of different localities.

[1] *Account of the Skerryvore Lighthouse.* By Alan Stevenson, LL.B., F.R.S.E. Edinburgh, 1848.

In November 1817 the waves of the German Ocean overturned, just after it had been finished, the Carr Rock Beacon, a column of freestone 36 feet high and 17 feet at the base, which was the largest size that the rock would admit of. The diameter at the level of high water was 11 feet 6, and at the plane of fracture 12 feet 9 inches.

*Modifying Influence of the Configuration of Rocks on Breaking Waves.*—When the history of this beacon is contrasted with the records which have been preserved of the extraordinary structures that were erected on the Eddystone by Winstanley, we cannot help suspecting that that rock must be of peculiar configuration, by which the force of the waves against the buildings which have been successively erected on it is modified, or to some extent diverted. This elaborate, though unsuitable, design (*vide* Plate XIII.) withstood the assaults of no fewer than eight winters. As the additions which he made from time to time to his original tower were in many instances anything but improvements, it may be questioned whether its fate (which was the result of an almost preternatural storm) was not accelerated by those injudicious alterations. His first year's work was a tower 12 feet high and only 14 feet diameter at the base, yet this stood during the whole of the first winter. The next year it was increased to 16 feet at the rock, a *polygonal* form being adopted, with an open gallery and vane with large ornamental scrolls, in all a height of 80 feet. This also stood for a winter. The next year it was increased to 20 feet at the rock by an outer ring of masonry, and the extreme height was raised to 120 feet. The open gallery and polygonal form were still retained; and numerous obstructive stages, a bluff projecting house for fishing, square chimney stalks, and colossal scrolls, were added. In spite of its

great leverage and the extent of its surface, this uncouth structure, above which the sea was said to rise more than 100 feet, stood, strange to say, for other four years, and disappeared only in November of the fifth winter, during one of the greatest storms ever experienced in this country, and of which I have already given an account in Chapter II.—from the records of which I think it may fairly be questioned whether Winstanley's work was really knocked down by the sea, or was overturned by the violence of the wind.[1] The next lighthouse was Rudyerd's, which, at the level of the top of the rock, was about 22 feet diameter, with a height of about 80 feet, and, although consisting largely of timber, stood forty-six years, when it was unfortunately destroyed by fire. It is further remarkable that, while at the building of the Bell Rock three stones, all dovetailed, wedged, and trenailed, were lifted after they had been permanently set, and at the Carr Rock Beacon twenty-two stones were displaced during its construction, there was no instance of any but loose, unset blocks having been moved during the erection of the Eddystone, although the stones were of very similar weight, and fixed in much the same manner. Smeaton mentions that "after a stone was thus fixed we never, in fact, had an instance of its having been stirred by any action of the sea whatever."[2] During the third winter at the Carr Rock nine stones, half a ton in weight, which were dovetailed, wedged, and trenailed, were removed *at the level of low-water neaps.* The trenails were all broken. *At* 2½ *feet above the mean level of the sea* five stones were in like manner moved, and during the fourth winter seven other stones were moved at a height of *three*

[1] *An Historical Narrative of the Great and Tremendous Storm which happened Nov.* 26, 1703. London, 1769. P. 148.

[2] *Account of the Eddystone*, p. 132.

*feet above the high-water level.* There seems, therefore, good reason for believing that the form of the Eddystone rock sheltered, to some extent, the structure that rested upon it. I may also mention that my friend Captain Fraser, who was engaged in the arduous work of erecting a lighthouse on the Alguada reef in India, entertains somewhat similar views regarding the Eddystone rock.

Additional and very remarkable corroboration of these views has also been afforded by the experience derived in the course of construction of the Dhuheartach lighthouse, which was finished in 1872, after having occupied five working seasons.

The Dhuheartach rock lies about 15 miles to the W.S.W. of Iona, in Argyleshire. It is 220 feet long and about 30 feet high, the tower being raised to the height of 130 feet above the sea. The rock, which is of an elliptical form, is everywhere surrounded by deep water. During a summer gale *fourteen* stones, each of two tons, which had been fixed in the tower by joggles and Portland cement at the level of 37 feet above high water, were torn out and swept off the rock into deep water. (*Vide* Plate XIII.)

Now, it is a remarkable fact that the level above the sea at which these blocks were removed by a summer gale is the same as that of the *glass panes* in the lantern of Winstanley's first lighthouse, which nevertheless stood successfully through a whole winter's storms. And in the tower, as last constructed by Winstanley, there was an open gallery at the same level as the former lantern, above which the cupola and lantern were supported, and which stood for four winters. In other words, at the same level at which thin panes of crown glass stood successfully for a winter at the Eddystone, and at which for other four winters the open gallery, with closed-in cupola

above, stood without damage, the fourteen joggled stones of two tons each were all swept away at Dhuheartach.

The conclusion, then, which is fairly deducible from these facts is, that *the impact against a lighthouse depends upon the relation subsisting between the height of the waves at the place and the height and configuration of the rock above and below low water, and perhaps also on the configuration of the bottom of the sea at the place.*

Thus, while the rock at Dhuheartach, from its height above the waves, forms a protection against the smaller class of waves, it operates as a dangerous conductor to the largest waves, enabling them to exert a powerful action at a much higher level than they would attain had the rock been lower. Hence the fact that the highest levels at which set stones were moved at the Carr Rock was 3 feet above high water, and at Dhuheartach 37 feet above high water, may be accounted for by the different configurations of the rocks, without assuming that the waves are exceptionally high at Dhuheartach. Plate XIII. will be found to exhibit an interesting view of these and other similar lighthouses, all laid down to the same scale.

It is of great importance that these facts should be kept in view, and that the Eddystone should not be regarded as a safe model for imitation at all rocks which are exposed to a heavy sea. Smeaton's tower has, since the proof-sheets of the third edition of this book were passing through the press, been taken down, not so much owing to failure in the structure, but because the rock on which it stood had been undermined; and a new tower has been erected from designs by Sir James Douglass on a rock near the old site.

*Different Forces which assail the Masonry of Harbour Works from the outside.*—The determination of the stability

of a practically monolithic mass, such as the Eddystone or Bell Rock Lighthouse, though difficult enough, is, however, of a simpler nature than that of the disconnected materials of a harbour work. In the masonry of lighthouses the sea is excluded from the joints of the stones, but in many harbour works the jet of water enters freely into the interior of the masonry, and introduces such complexity into the question as to render it impossible, at least in the present imperfect state of our information, to give any rules for directing the engineer. I can only, therefore, simply point out the nature of the different forces which enter into the question of the stability of such loosely built structures, so as to show in what directions the sea attacks the work. The impact of the waves against the outside of a sea-wall or pier gives rise to four distinct forces, namely—1st, The direct horizontal force which tends to shake loose, or drive in, the blocks of which the masonry consists. 2d, The vertical force acting upwards on any projecting stone or protuberance, as well as against the lying beds of the stones. 3d, The vertical force acting downwards, which results either from the wave breaking upon the toe of a talus wall, or from its passing over the parapet and falling upon the pitching behind, so as to plough it up. 4th, The *back-draught*, which tends by reaction from the wall to remove the soft bottom, and in this way to undermine the lower courses of the work.

It may be concluded from the above that the points which require to be most attended to are—the contour and quality of masonry of the wall itself—the parapet, which, if not of proper form, or of insufficient height, leads to damage of the pitching behind it; and lastly, the foundation-courses, in the design and construction of which, if similar precautions be not attended to, underwashing of the bottom may in some

situations take place, so as to leave the lowest courses without protection.

1. *Horizontal Force against Sea-Walls—Flush Dynamometer—Observations on Force at different heights.*—In 1858 I made some experiments at Dunbar, which were continued till the completion of the new wall there, in order to ascertain the relative forces exerted at different levels. The first series began with the old curved sea-wall (Fig. 16). For this

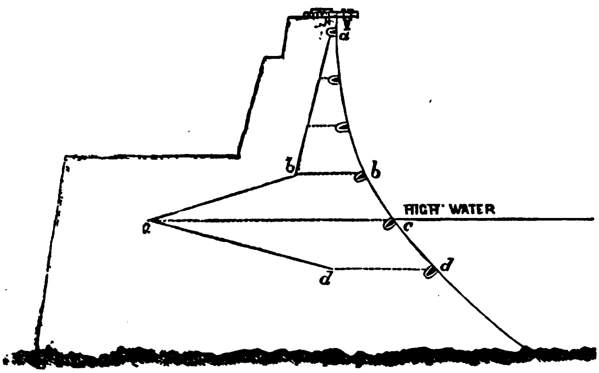



Fig. 16.

purpose it was necessary to sink the dynamometers into the masonry, so that their discs should be nearly *flush* with the line of wall. As Figs. 17, 18 represent those flush dynamometers both in elevation and section, no further description of them seems necessary. The holes *a a a* (Fig. 18), shown in the under side of the rod, were made for holding shot which was expected to drop out when the rod was pushed so far out as to leave them unsupported. This arrangement, which promised to be a good check on the indications of the leathern index, was not, however, found to answer; but my friend Mr. Alan Brebner, C.E., has suggested that a cylinder of wax might indicate well, by having its surface scratched by

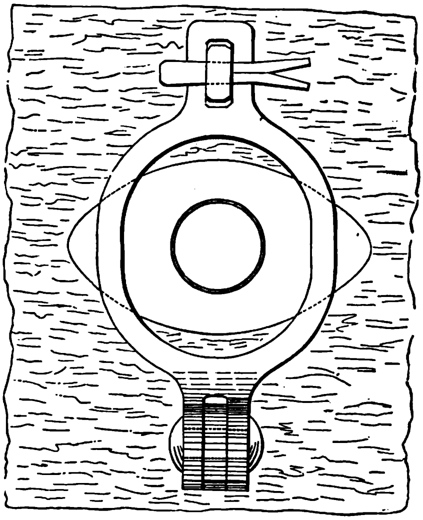


Fig. 17.—Elevation.

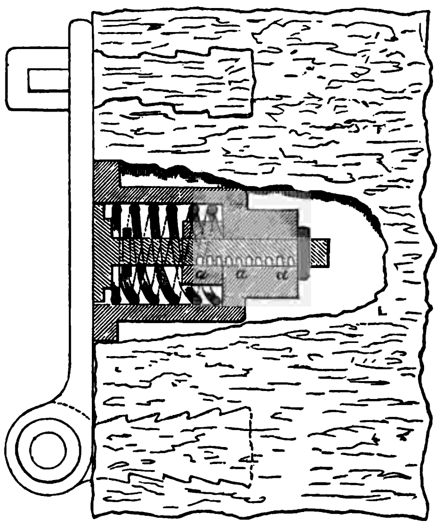


Fig. 18.

a needle attached to the movable end of the spring. The cavities in the stone into which the flush dynamometers were sunk were made larger on the upper side than was necessary for holding them, in order to furnish at the top a reservoir for air, the compression of which on the impact of the wave against the disc permitted it to pass inwards on the stroke of the wave. Owing to a most unfortunate uncertainty regarding the readings of some of the instruments employed in these observations, and which was only discovered when the results, extending over a period of years, were examined for reduction, it would not be warrantable to deduce from them any rule or formula. The source of error having been now discovered, other results, on which full reliance can be placed, will, at some future period, it is hoped, be obtained; but the lines *b b*, *c c*, *d d* (Fig. 16), may be held to represent generally the nature and directions of the forces.

Before leaving this part of the subject I may refer to the action of the waves of the tideless Mediterranean. When in Italy, in 1864, I made the accompanying sketch (Fig. 19), which shows the scooping out of the solid rock during the lapse of an unknown number of centuries on the coast between Mentone and Ventimiglia, and which illustrates well the sudden reduction of force which, it is known, takes place immediately below the water level.


Fig. 19.

In 1838 I made several cross sections of the forms which the waves scooped out of the clay banks of the Bristol Channel

at Cardiff moors. Fig. 20 represents the general form of profile.

2. *Observations on Vertical Force.*—Simultaneously with the other observations at Dunbar, two marine dynamometers, of the common construction (*a*, Fig. 16), were fixed to a piece of wood which was bolted to the top of the cope of parapet. The instruments were fixed with their discs projecting over the edge of the cope, and pointing downwards so as to ascertain the upward force of the ascending body of water and spray. The *maximum vertical force* recorded at the cope of the wall,

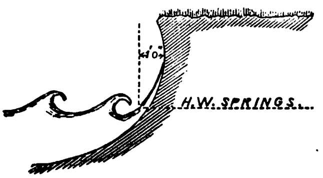



Fig. 20.

*a*, Fig. 16 (23 feet above the sea at the time that the observation was made), was upwards of one ton (2352 lbs.) per superficial foot, while the greatest *horizontal* force recorded by the highest of the *flush* dynamometers, which was fixed 18 inches lower in the stone immediately below the cope, never exceeded 28 lbs. The great vertical force at and near the top may, at first sight, appear to be somewhat anomalous, but it must be recollected that the discs of the dynamometers were in the one case parallel, and in the other opposite, to the line of direction of the particles, as altered by the wall. *The vertical force tending to raise the projecting cope of a sea-wall is therefore, in such a situation as this, about* 84 *times greater than the horizontal force tending to thrust it inwards.* This shows that the higher the spray is allowed to rise the less force will be exerted horizontally against the masonry near the

top, unless any part of it projects beyond the face of the wall. Therefore, to make what may be called an easy wall for the sea, the outer edge of the cope should be slightly rounded, or the stone itself should be set an inch or two back from the face of the wall.

*Danger from Cavettos and String-courses on Sea-Walls.*—It follows, further, from these observations that not only should all overhanging string-courses be avoided, but that even very rough ashlar stones with large protuberances on the seaward face are undesirable. At the harbour of Stonehaven (Fig. 21)

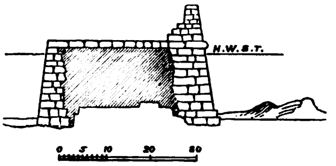


Fig. 21.

a "string" or "bottle" course had to be hewn off, in order to prevent the concussions which took place during storms, and which were so great as to shake the superincumbent masonry. Even such small objects as an upright pole have been found, from their leverage, by their catching the spray, to disturb the masonry to which they were fixed. This was proved at Cockenzie, East Lothian, where a flagstaff had to be removed on account of its shaking the parapet when the waves struck it.

*Observations of Rise of Spray on Vertical and Curved Walls.*—In connection with the Dunbar experiments, it may be added that the spray—on an average of seventeen observations taken roughly—*was found to rise on the hollow curved wall about seven times higher than the waves which projected it, and on the vertical wall,* taking a mean of twenty-three observations, *it rose* 6.6 *times higher.*

3. *Vertical Force acting Downwards—Damage to Roadway.*

—The water, after striking upon the sea-wall, rises in large volumes above the parapet, and, descending with great force, dashes against the pitching of the roadway. If the pitching stones are not sufficiently heavy and closely assembled they may be ploughed up by the descending water, when the interior of the work is at once laid open to the destroying element. The late Mr. James Bremner of Wick,[1] thus describes the disastrous consequences which resulted from the breaking up of the roadway pitching of the old harbour of Pulteneytown, and the manner in which he protected it from after damage:—"By the 20th of September in that year" (1827) "the whole operations would have been substantially completed, but, on the 10th of that month, a violent storm arose, during which, notwithstanding precautionary means, which I had always provided against ordinary storms, by blocking up and forming substantial obstructions against the sea, for temporary defence, an extent of building of not less than 100 feet of the breakwater-head was, during one tide, swept away, and reduced to the level of the water."

"To prevent the recurrence of such misfortunes, the author reared a wall, of large rough stones, under the parapet; he compacted the roadway pitching with fir-wood wedges, on which cills 1½ inch broad, running along the roadway, were spiked down at distances 10 inches apart. On these cills boards of an inch thick were fixed, and closely joined together, the outer ends lying to the foot of the parapet, while the inner ends reached half-way over the coping of the front wall, so that the sea, falling over the parapet, was not permitted to strike the pitching."

4. *Horizontal Force of the Back Draught of the Wave.*—

[1] See *Treatise on the Planning and Building of Harbours, etc.* By James Bremner, M.I.C.E. Wick, 1845.

Dynamometers having their discs *facing the wall* were fixed to a pile placed immediately outside of the Dunbar bulwark, while others were fixed to the same pile with their discs pointing seawards. On one occasion, owing no doubt to the concentration of the watery filaments by the sea-wall, the force of recoil was equal to one ton, while the direct force of the waves before they had reached the wall was only 7 cwt. per square foot, or *the force of recoil was equal to three times the direct force.*

*Destructive Forces acting within the Masonry.*—Within the masonry, as well as without, the waves exert force in the following different ways :—1st, By the propagation of vibrations produced by the shock of the waves on the outer or sea-wall, through the body of the pier to the inner or quay-wall; 2d, by the direct communication of the impulses through the particles of the fluid occupying the interstices of the hearting, so as to act against the back joints of the face stones of the quay; 3d, by the sudden condensations and expansions of the air in the hearting, so as to loosen, and at last to blow out, the face stones of the quay, combined with, 4th, the hydrostatic pressure of the water, which is forced through the sea-wall, and, from want of free exit, is retained and acts as a *head* at the back of the quay, and which, however small in quantity, will, as in a Bramah press, act upon all surfaces exposed to its pressure, however great those surfaces may be. The three last causes are probably the most efficient agents in the work of destruction.

*Examples of Piers of Insufficient Width destroyed by Forces acting within the Masonry.* — Although there is no instance on record of any pier being overturned by one stroke of the waves, and it may generally be concluded that, in all ordinary exposures, harbour works capable of affording the accommodation required for shipping will

necessarily possess sufficient mass to resist destruction in this wholesale manner, yet many instances have occurred of large portions of masonry being moved *en masse* by a single stroke of the sea. As an example occurring in a comparatively sheltered locality, we may adduce the harbour of Millport, in the Isle of Cumbrae. In December 1862 Mr. Jamieson, the harbour-master, was on the pier when a very heavy wave struck the parapet with most unusual violence, throwing up a jet of water which he described as "half spray, half solid," to the height of 10 or 12 feet above it. The wave covered to the depth of about 18 inches that part of the roadway at the outer end which had not the protection of a parapet, and moved (not rolled) a mass of sheet lead weighing 12 cwt. along its surface, until it came in contact with one of the mooring pauls, which arrested its motion. On examining the masonry, which he did as soon as the waves would permit, he found that a large portion of the parapet had been thrown back.

While the parapet remained in the same state in which the storm left it I had an opportunity of measuring it with Mr. Jamieson, and found that 33 feet in length had been bodily thrust backwards to the maximum extent in the middle of 4 inches. The level of the bottom of the parapet was, according to Mr. Jamieson, about 7 feet above ordinary springs, and I found it to be 6 feet 3 inches above the level of the *lepas* or barnacle shell. The masonry, which is freestone, was all joggled with cubes of greenstone, and there were side straps on the cope. The parapet, 5 feet 5 inches in height, consisted of five courses, including the cope, and Mr. Jamieson said it was nearly of solid ashlar, there being hardly any rubble hearting.

It sometimes happens that from the forces acting within the face-walls to which we have referred, serious damage has

resulted if the pier be of insufficient width. One case of this occurred at an exposed port on the east coast of Britain. Without entering upon the details of this work, it is sufficient to mention that the pier, which had a sea-wall curved vertically to a radius of 32 feet, received much injury during the execution of the work. As the damage gave rise to certain legal questions between the contractor and the promoters, an investigation was made with reference to those questions, when the following interesting information was obtained:—It was found, after the storm which occasioned the greatest damage, that of 230 feet of finished pier about 120 feet had been demolished, and the materials formed a heap, the seaward face of which had assumed a natural slope or angle of repose of about 4 to 1. After a minute inspection of the *parapet* wall of that part of the pier that had been left standing not the smallest appearance of failure could be anywhere detected. The *sea-wall* was in like manner unaffected, with the exception of one or two points where some appearance of starting or very slight shifting was noticed. The *pitching* of the roadway was also quite sound and entire. But, on turning to the sheltered side of the pier forming the *quay*, the work presented a very different aspect. This wall was very much shattered for a distance of about 140 feet. Most of the stones in the facework were skirted or cracked at the corners, and had evidently been moved in their beds to a greater or less extent, and some of them, at and near the middle courses or half-way up the wall, had been thrust out as much as $\frac{7}{8}$ of an inch beyond the face line. It was found, on examining the heap of debris of that part of the work which had been thrown down, that the lower courses of the quay-wall for about six feet above the foundation had not been overthrown, though they were much shattered, and the general line of the

masonry was also greatly distorted. The cause of the damage, in the opinion of those resident at the place, was want of strength in the inner or *quay-wall* to resist the forces which were propagated through the pier from the outside. The truth of this statement was fully borne out by the fact that the damage occasioned by *five* different storms had in every instance made its appearance first on this the *inner* wall. The breadth of the pier at the level of the roadway was 26 feet 4 inches, and at the level of high water 28 feet.

Another case, which also gave rise to legal questions, was that of a harbour situated also on the east coast of Britain, which, although open to the N.E. swell, was nevertheless to some extent protected by a considerable reef of rocks extending in front of it. It differed from the former case in being of very bad workmanship. The stones composing the face of the sea-wall were imperfectly dressed, being all "*lean to the square.*" The hearting had been carelessly thrown in, without hand packing, and the quay-wall was also very ill dressed, and from an inspection of the work after the accident there did not seem to have been any regular *backing.* While walking along the roadway of the pier before the storm took place which did the damage, I was surprised on seeing jets of air and water suddenly projected into the basin of the harbour with a loud report. These were found to proceed from the stroke of the waves on the sea-wall outside, which was transmitted through that wall, and through the hearting and quay-wall. The waves at the time did not much exceed 3 or 4 feet in height, and yet the impulse of almost every one was propagated through the pier as if through wicker-work, making its presence evident by the jets of air and water, some of which extended into the basin of the harbour to probably 20 feet beyond the front of the quay. The width of the pier

(Fig. 22) was 24 feet at the level of the roadway. During a severe storm from the E.N.E., which took place some time

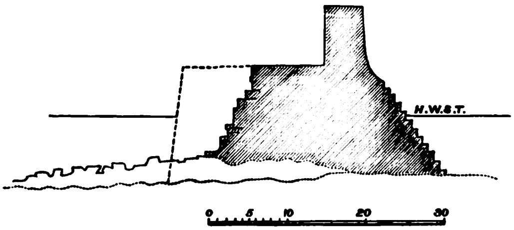


Fig. 22.

after the work was finished, the greater portion of this work was thrown down, and it was observed that the *quay-wall was at some places the only part that gave way.* The spray during the gale rose about 20 feet above the top of the parapet. A sailor resident at the place stated that during the gale, but before any damage had taken place, he repeatedly saw water spouting up through the pitching (close to the cope of the quay-wall) to the height of about 16 feet above the roadway. This jet would of itself indicate a pressure against the back of the quay, even as high up the wall as the cope itself, of about half a ton on the square foot.

Another instance of a similar kind was seen at a harbour on the west coast of Britain (Fig. 23), where the length of

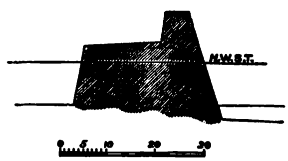


Fig. 23.

fetch was only 40 miles. The breadth at level of high water was 26 feet, and the workmanship seemed to be of good

quality. In this case the pitching was the first part that was seen to give way by those resident on the spot. It was forced upwards by the air and water in the interior. Ultimately the sea and the quay walls were also much damaged.

*Minimum Width of Piers in German Ocean.*—After comparing different piers exposed to the German Ocean, where we have most examples, and from careful consideration of the other data, I should not feel disposed to recommend that vertical piers, fully exposed to the *ordinary* waves of that sea, consisting of the ordinary kind of dry masonry, should be less than from 35 to 45 feet broad at the level of high water. But, of course, this remark does not apply to anomalous cases where the sea is exceptionally high, but, as stated, to works exposed to the ordinary waves.

*Examples of Damage from Rarefaction of the Air outside of the Masonry.*—Outer sea-walls, as well as the inner quay-walls, are also liable to damage from pneumatic action *ab infra.* The sudden "*back draught*" occasioned by the relapse of a heavy wave after it has broken against a building, produces, according to the late Mr. Walker,[1] a certain amount of rarefaction in the surrounding air. Mr. Walker seems to have been the first to notice the existence of this phenomenon, which was manifested in a remarkable and extraordinary manner at the Eddystone Lighthouse during a heavy sea in the year 1840. On that occasion the entrance door of the tower, which was made secure by strong bolts against the force *ab extra,* was driven outwards by a pressure acting *from within the tower.* The strong bolts and hinges are stated to have been broken. This interesting and almost incredible incident seems to prove that, by the instantaneous sinking of the wave, the atmospheric pressure was suddenly, and to a

[1] *Inst. Civ. Eng.*, vol. i. p. 115.

very considerable extent, removed from the air on the outside of the door in the masonry of the upper part of the tower. As the air within the tower continued still to receive its usual pressure, which would be communicated freely from the windows and lantern door in the *upper* parts of the building, it appears suddenly to have burst the lower door outwards in order to supply the partial vacuum, and thus to

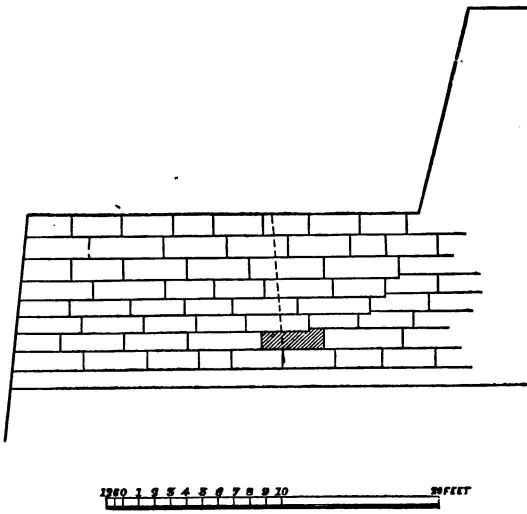


Fig. 24.

restore the equilibrium of the air outside and inside of the building which had been disturbed by the sudden subsidence of the wave. It is perhaps from this, among other causes, that stones sometimes start out of the facework of sea-walls in a very unexpected manner, and, if not speedily noticed, soon project so far as to allow the waves to remove them altogether, when the worst consequences may ensue.

The accompanying diagram (Fig. 24) represents a case of

this which occurred at the harbour of Buckie, in Banffshire, in which the combined effects of condensation and back draught started a stone from its bed in the face of the end of the pier. The whole of the masonry had been finished several months before, and had encountered successfully two or three very hard gales, when it was noticed, after the occurrence of another heavy sea, that the stone, which is hatched black in the diagram, had started from its bed, and was projecting several inches out from the wall. The stone, which was a stretcher, 4 feet long and 14 inches thick, had no doubt been originally set slack in the work. A heavy wave had first driven water and condensed air through the joints among the backing, and then the sudden subsidence of the wave had produced a rarefaction, and lastly the head of water and the condensed air in the inside of the work had, in bursting outwards, started the stone from its bed. It was made secure by a vertical bolt driven from the coping course in the direction shown by the dotted line. It appears probable, then, that the stones composing the masonry of sea-works may be subjected to simultaneous expansions of the condensed air behind, and rarefactions occasioned by the collapse of the wave in front.

*Buildings on a Rock Foundation—Selection of Stones.*—Having now adverted to the different forces to which marine works are exposed, I shall next consider what kind of design is most suitable where the bottom consists of hard rock. Such a foundation will render unnecessary any precautions arising from the wasting of the bottom, and, *cæteris paribus*, there does not seem to be any reason for preferring a talus to a vertical wall.

The question of preference where the rock is sound will, in the main, depend upon the kind of material which can be

obtained. Should the stone be scarce or costly, and the quality such as to warrant the introduction of masonry of the best description, the vertical wall may be found to be the most economical. Where freestone is to be used it is not only desirable that it should be got in large blocks, but that the face stones should possess considerable hardness. All materials which are subject to decay from atmospheric influence should either be entirely rejected or reserved for the interior of the work. Special care is also necessary in selecting the stones for the lower courses, and all the more so if the beach consist of hard gravel or boulders. Where these occur on an exposed coast, granite or other hard stone should always be preferred. There are beaches where even blocks of greenstone waste away with alarming rapidity by the action of rolling stones.

Cessart found timber to resist abrasion from rolling gravel ten times longer than limestone. The timber planking which he used was fixed *vertically* on the masonry.[1]

In 1870 I noticed a somewhat remarkable fact at the foundations of the old castle at Sandgate, near Folkestone. The granite blocks forming the outer scarcements had been bound together with iron bars, secured with lead. The lead had, owing no doubt to slower oxidation, held its ground against the sea better than either the iron or the granite, and it stood up about $\frac{1}{8}$ inch higher than the surface of the more rapidly wasting materials.

*Relative Durability of Different Rocks.*—The superiority of granite to greenstone is proved by the following experiments on the times required to abrade $\frac{1}{16}$ inch off each kind of stone. They were loaded with the same weights and the same grinding agents were used, and with equal cubes of each material :—

[1] *Ouvrages Hydraul.*, p. 83.

30 minutes were required for Queensferry (Carlin Nose) greenstone.
40 „ for greenstone from Barnton, near Edinburgh.
60 „ for Peterhead granite.

Mr. Murray of Sunderland also established, many years ago, the superior power of resistance possessed by granite over greenstone.

*Strength and Hardness of Materials.*—At Anstruther harbour the freestone of the district was, from motives of economy, employed for the sea-wall, in consequence of the failure of the rock from the excavations. Stones thrown forcibly up by the sea against the new sea-wall caused fractures of the face-stones, which gradually falling out produced extensive damage to the pier itself.

*Wasting of Rock Foundations.*—Rocky ledges often break up at the foundation of an exposed sea-wall, owing to the heavy fall of water in front of the work. An occasional examination should from time to time be made, to ascertain whether this dangerous action is taking place, as it may lead at last to undermining of the wall.

*Profile when Materials are Large and Unworkable.*—If the materials are abundant, but of an unworkable nature, a long talus wall will be found most economical. For such walls the rate of slope must depend very much upon the exposure of the place and upon the plentifulness of rubble stone hearting. The easily-dressed and naturally flat-bedded materials, which the stratified rocks of the secondary formation very often furnish, are especially applicable to the construction of vertical walls; while the uncouth blocks of the primary and igneous formations are better suited for talus walls. Such rocks as gneiss, the schists, basalts, greenstones, porphyries, and the

tougher kinds of granite, are best fitted for this purpose. With some of these rocks, the angularity of the pieces, and the excessive difficulty and uncertainty of dressing, render it necessary to assemble them without almost any alteration of their shape, so as, by an adaptation of their salient and re-entrant angles, to make a kind of random rubble face-work. In this kind of work mortar was formerly very seldom employed, but Mr. Hartley first, and afterwards, at Holyhead, Sir J. Hawkshaw, successfully introduced rubble, consisting of enormous unsquared masses of rock set in hydraulic mortar.

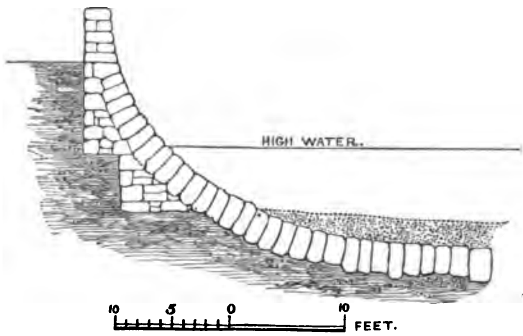



Fig. 25.

The *parapet*, which usually consists of squared masonry on the outside, surmounted by a heavy cope, used generally to be the only part of sea-works which was set in lime-mortar, the joints being pointed or lipped with Roman or Portland cement. The valuable qualities of the limestone from Halkin Mountain in North Wales, Aberthaw in Glamorganshire, and more especially Arden in Ayrshire, are generally known, and render them well suited for building parapets, but Portland and Zumaya cements are of all mortars undoubtedly the best.

*Profile when Materials are of Small Size—Cycloidal Curve.*

—Where the materials are light and of small sizes, it is desirable to design the work so as to equalise the action of the sea over the whole work, and not to concentrate it against any particular place. Mr. Russell states that the cycloidal form was recommended for this purpose by Franz Gerstner of Bohemia. The only instance of the adoption of this curve with which I am acquainted (Fig. 25) is in a sea-wall which was erected at Trinity, near Edinburgh, by the late Mr. Robert Stevenson, in 1822.

*Table of Properties of different Rocks.*—In judging of the qualities of different quarries for harbour purposes, the importance of a high specific gravity should not be overlooked. The accompanying table is useful in showing this. When $s$ represents the specific gravity, $n$ the number of cubic feet in a ton in air, $n'$ the number of cubic feet in sea water, $a$ side of cube weighing a ton in water, and $w$ weight of a ton-block in water—

$$n = \frac{2240}{s \times 62.5} \qquad n' = \frac{2240}{(s \times 62.5) - 64.25}$$

$$a = \sqrt[3]{\frac{2240}{(s \times 62.5) - 64.25}} \qquad w = \frac{2240 - 64.25\,n}{2240}$$

The specific gravities of the rocks marked thus * are given by the Parliamentary Commission which was appointed to report on the best stone for the new Houses of Parliament, and the specific gravity of Beton is assumed on the authority of Minard in his *Cours de Construction.* All the others I took by means of a spring balance—a method which I strongly recommend, from the quickness as well as accuracy with which the specific gravities are obtained. Any piece of rock, however rough and unsymmetrical, may be readily suspended from the balance, and the reading on the

scale at once noted. The stone is next immersed in water, and its weight again noted, the whole process of getting the weights in air and water not occupying so much as one minute. Dressing and weighing a cubic foot of stone, which is so common with quarry masters, is both an inaccurate and tedious method, which need never be resorted to.

Mr. C. P. Cotton of Dublin has proposed to use the sulphate of barytes (heavy spar), which abounds in the south and south-west of Ireland, as a substitute for ordinary stone in rubble or concrete. Its very high specific gravity (4.4) renders it very suitable for beacons in exposed situations. Mr. Cotton estimates the weight of barytic concrete at 252 lbs. per cubic foot, which would very nearly double the weight of the structure.—*Trans. Instit. Civ. Eng., Ireland,* 1870.

In some very exposed situations *iron rubble,* consisting of pig-iron set in Portland cement, might be used for building beacons or other structures in the sea.

## TABLE OF PROPERTIES OF DIFFERENT KINDS OF ROCK.

| NAMES OF ROCKS. | $s$ | $s \times 62.5$ | $\frac{2240}{s \times 62.5} = n$ | $\frac{2240}{(s \times 62\frac{1}{4}) - 64.25} = n$ | $\sqrt[3]{\frac{2240}{(s \times 62.5) - 64\frac{1}{4}}}$ | $\frac{2240 - 64\frac{1}{4}\,n}{2240}$ | Side of a Cube weighing 1 Ton in Air. | Loss of Weight of a Ton Block by immersion in Sea Water. |
|---|---|---|---|---|---|---|---|---|
| | Spec. Grav. | Weight of a Cubic Foot in Air. | No. of Feet to a Ton in Air. | No. of Feet to a Ton in Sea Water, Sp. Gr. 1.028. | Side of Cube corresponding to last Column. | Weight of a Ton Block in Sea Water, Sp. Gr. 1.028. | | |
| | | Lbs. | Cub. ft. | Cub. ft. | Lineal ft. | Ton. | | |
| Basalt (porphyritic) ... | 2.99 | 186.87 | 11.9 | 18.26 | 2.63 | .658 | 2.283 | .342 |
| Greenstone ... ... | 2.92 | 182.50 | 12.2 | 19.00 | 2.66 | .650 | 2.302 | .350 |
| Syenite ... ... ... | 2.91 | 181.9 | 12.3 | 19.04 | 2.67 | .647 | 2.308 | .353 |
| Clay-slate ... ... | 2.90 | 181.25 | 12.3 | 19.15 | 2.67 | .647 | 2.308 | .353 |
| Mica-schist ... ... | 2.89 | 120.6 | 12.4 | 19.24 | 2.68 | .644 | 2.315 | .356 |
| Gneiss ... ... ... | 2.82 | 176.2 | 12.7 | 20.00 | 2.71 | .635 | 2.333 | .365 |
| Amygdaloidal greenstone | 2.75 | 171.87 | 13.0 | 20.81 | 2.75 | .627 | 2.351 | .373 |
| Chlorite-schist ... ... | 2.74 | 171.25 | 13.0 | 20.93 | 2.75 | .627 | 2.351 | .373 |
| Greywacke ... ... | 2.73 | 170.62 | 13.1 | 21.06 | 2.76 | .624 | 2.357 | .376 |
| Clinkstone ... ... | 2.73 | 170.62 | 13.1 | 21.05 | 2.76 | .624 | 2.357 | .376 |
| Red granite ... ... | 2.71 | 169.37 | 13.2 | 21.30 | 2.77 | .621 | 2.362 | .379 |
| Slate (old red sandstone formation) ... | 2.71 | 169.37 | 13.2 | 21.30 | 2.77 | .621 | 2.362 | .379 |
| Chalk ... ... ... | 2.70 | 168.75 | 13.2 | 21.43 | 2.77 | .621 | 2.362 | .379 |
| White primary limestone (marble) ... | 2.70 | 168.75 | 13.2 | 21.43 | 2.77 | .621 | 2.362 | .379 |
| Red primary limestone (marble), with crystals of augite embedded | 2.66 | 166.25 | 13.4 | 21.96 | 2.80 | .615 | 2.375 | .385 |
| Chlorite ... ... ... | 2.64 | 165.00 | 13.5 | 22.23 | 2.81 | .612 | 2.381 | .388 |
| Granular quartz rock ... | 2.63 | 164.37 | 13.6 | 22.37 | 2.82 | .610 | 2.387 | .390 |
| Grey granite ... ... | 2.61 | 163.12 | 13.6 | 22.65 | 2.83 | .610 | 2.387 | .390 |
| Flinty slate ... ... | 2.57 | 160.62 | 13.9 | 23.24 | 2.85 | .601 | 2.405 | .399 |
| Red felspar porphyry ... | 2.55 | 159.37 | 14.0 | 23.55 | 2.86 | .598 | 2.410 | .402 |
| Pitchstone ... ... | 2.53 | 158.12 | 14.1 | 23.86 | 2.88 | .595 | 2.416 | .405 |
| Serpentine ... ... | 2.46 | 153.75 | 14.5 | 25.02 | 2.92 | .584 | 2.438 | .416 |
| Compact felspar ... | 2.45 | 153.12 | 14.6 | 25.20 | 2.93 | .581 | 2.444 | .419 |
| Sandstone ... ... | 2.41 | 150.62 | 14.8 | 26.00 | 2.96 | .575 | 2.455 | .425 |
| Roestone (oolite) ... | 2.36 | 147.50 | 15.1 | 26.88 | 2.99 | .567 | 2.472 | .433 |
| Beton ... ... ... | 2.2 | 137.05 | 16.3 | 30.6 | 3.13 | .532 | 2.585 | .468 |
| Magnesian limestone* ... | 2.18 | 136.25 | 16.4 | 31.11 | 3.14 | .529 | 2.541 | .471 |
| Oolite* ... ... ... | 2.05 | 128.12 | 17.4 | 35.07 | 3.27 | .501 | 2.591 | .499 |
| Parrot coal (American) | 1.54 | 96.25 | 23.3 | 70.00 | 4.12 | .331 | 2.856 | .669 |
| Bituminous shale ... | 1.50 | 93.75 | 23.8 | 75.93 | 4.23 | .317 | 2.876 | .683 |
| Cannel coal .. ... | 1.24 | 77.50 | 28.9 | 169.05 | 5.53 | .171 | 3.069 | .829 |

NOTE.—This table is calculated for sea water of the specific gravity of 1.028, or $64\frac{1}{4}$ lbs. to the cubic foot.

The following Table, showing the pressure of sea water per superficial foot for different depths, will be found useful in connection with that given above :—

TABLE showing Pressure of Sea Water per Superficial Foot for Different Heads. Specific Gravity taken at 1.028.

| Height in Feet. | Pressure in lbs. per Sq. Foot. | Height in Feet. | Pressure in lbs. per Sq. Foot. | Height in Feet. | Pressure in lbs. per Sq. Foot. | Height in Feet. | Pressure in lbs. per Sq. Foot. |
|---|---|---|---|---|---|---|---|
| 1 | 64¼ | 26 | 1670½ | 51 | 3276¾ | 76 | 4883 |
| 2 | 128½ | 27 | 1734¾ | 52 | 3341 | 77 | 4947¼ |
| 3 | 192¾ | 28 | 1799 | 53 | 3405¼ | 78 | 5011½ |
| 4 | 257 | 29 | 1863¼ | 54 | 3469½ | 79 | 5075¾ |
| 5 | 321¼ | 30 | 1927½ | 55 | 3533¾ | 80 | 5140 |
| 6 | 385½ | 31 | 1991¾ | 56 | 3598 | 81 | 5204¼ |
| 7 | 449¾ | 32 | 2056 | 57 | 3662¼ | 82 | 5268½ |
| 8 | 514 | 33 | 2120¼ | 58 | 3726½ | 83 | 5332¾ |
| 9 | 578¼ | 34 | 2184½ | 59 | 3790¾ | 84 | 5397 |
| 10 | 642½ | 35 | 2248¾ | 60 | 3855 | 85 | 5461¼ |
| 11 | 706¾ | 36 | 2313 | 61 | 3919¼ | 86 | 5525½ |
| 12 | 771 | 37 | 2377¼ | 62 | 3983½ | 87 | 5589¾ |
| 13 | 835¼ | 38 | 2441½ | 63 | 4047¾ | 88 | 5654 |
| 14 | 899½ | 39 | 2505¾ | 64 | 4112 | 89 | 5718¼ |
| 15 | 963¾ | 40 | 2570 | 65 | 4176¼ | 90 | 5782½ |
| 16 | 1028 | 41 | 2634¼ | 66 | 4240½ | 91 | 5846¾ |
| 17 | 1092¼ | 42 | 2698½ | 67 | 4304¾ | 92 | 5911 |
| 18 | 1156½ | 43 | 2762¾ | 68 | 4369 | 93 | 5975¼ |
| 19 | 1220¾ | 44 | 2827 | 69 | 4433¼ | 94 | 6039½ |
| 20 | 1285 | 45 | 2891¼ | 70 | 4497½ | 95 | 6103¾ |
| 21 | 1349¼ | 46 | 2955½ | 71 | 4561¾ | 96 | 6168 |
| 22 | 1413½ | 47 | 3019¾ | 72 | 4626 | 97 | 6232¼ |
| 23 | 1477¾ | 48 | 3084 | 73 | 4690¼ | 98 | 6296½ |
| 24 | 1542 | 49 | 3148¼ | 74 | 4754½ | 99 | 6360¾ |
| 25 | 1606¼ | 50 | 3212½ | 75 | 4818¾ | 100 | 6425 |

*Buildings on Soft or Sandy Foundations.*—It has been already shown that, irrespective of the quality of the masonry, the two points in the structure which are weak or dangerous are the *top* and *bottom* of the wall. With a hard rocky bottom, properly dressed, the risk of failure at the foundations is removed; on the other hand, where the shore consists of soft or rotten rock, moving shingle, or sand, it is obvious

that provision must be made against both those sources of evil. Indeed, if we consult the history of harbours, we shall find that the most frequent cause of damage is the corroding action of the waves reflected by the masonry against the shore.

*Profile of Conservancy, and Underwashing.*—The general slope of a fragmentary beach must depend upon the size and nature of the particles and the force of the sea. The dissimilarity between its slopes, near the levels of high and low water, arises from a decrease in the force of the waves, caused by their being broken before they reach the high-water mark. The great object, therefore, is to design the profile of the wall so as to alter as little as possible the natural symmetry of the beach. Where isolated rocks or large boulders are left projecting above the surface of a sandy shore, there will generally be formed around them hollows corresponding in depth and form to the kind of obstruction which the rocks present. The principal point in the design, therefore, is to avoid great and sudden obstructions to the movement of the water. The best form which could be adopted in any situation would, of course, be the contour of the beach itself; but this would answer no possible purpose; and, as the wall is to consist of heavy blocks of stone, instead of minute particles of sand, it is clear that a much steeper slope may be adopted than that which we may call *the profile of conservancy* of the shore, provided the lower part of the slope be flattened out so as to meet the sand at a low angle. The action of a bulwark is to arrest the waves before they reach the general high-water mark, and to change the horizontal motion of the fluid particles to the vertical plane, or to compel the waves to destroy themselves on an artificial beach consisting of heavy stones. To prevent underwashing, the two following requisites should therefore be, as

far as possible, secured :—1st, The foundation courses of the wall should rise at a very small angle with the beach, so that their top surfaces may be coincident with the profile of conservation of that portion of the beach out of which the wall springs; 2d, The outline of the wall should be such as to allow the wave to pass onwards without any sudden check till it shall have reached the strongest part of the wall, which should be placed as far from the foundation as possible.

*Loose Rubble a good Protection for the Foundations, and for acting as a cover for Bulwarks for protecting Land against the Sea.*—Loose blocks of angular rubble, furnish, in most cases, the best possible security when the soil is soft or friable, for the waves are swallowed up by the interstices. A regular sloping sea-wall or bulwark, with a smooth surface, becomes, when the soil is soft, a *double-edged sword* in working its own destruction at top and bottom; for it transfers the duty of destroying the waves from the masonry to the unprotected soil behind the top of the wall, and to the loose sand or gravel at the bottom of the wall. While the foundations are underwashed by the reaction upon the soft bottom, the upper parts of the masonry are deprived of support by the falling water and spray, which are led up by the masonry, and soon wash away the earthy soil at the top.

*Walls of Horizontal Curvature for protecting the Coast-line.*—But it must be further noticed that, if the wall be curved in the *horizontal* plane, or consist of kants inclined at an angle to each other, the foundations must be carried lower at the convex parts and at the salient angles, for at those parts there is a greatly increased scour. This concentration in the scouring action may be very satisfactorily seen at low water, where an isolated rock or a boulder of pyramidal form projects above

the surface of a sandy sea-beach. Pools of greater or less depth will always be found at the angles of the boulder, while at intermediate parts the level of the sand is much higher.

*Walls of Vertical Curvature.*—For the reasons which have been stated, it is plain that a vertical wall is, in most cases, unsuitable for a sandy beach. Instead of altering the direction of the wave at a distance from its foundation, the whole change is produced at that very point; and, unless the wall be founded at a considerable depth, its destruction is all but certain. Where the materials are costly, but admit of being easily dressed, I am disposed to think that a horizontal, or nearly horizontal, apron or platform of timber or masonry, connected with a vertical wall by a quadrant of a circle of sufficient radius, may be found answerable. Such a form will prevent, to a considerable extent, the danger of reaction, by causing the alteration in the direction of the wave to take place at that part where the wall is strongest, and which is also at the greatest possible distance from the toe or curb course. If the materials are abundant, and of a rough nature, a cycloidal wall with vertical and horizontal tangents, somewhat similar to that erected at Trinity, already referred to, may be adopted with advantage. But a very serious objection to all forms of curved walls, unless the radius be large, is the weakness which results from the use of wedge-shaped face-stones. The impact of the sea on materials of that form may be compared to a blow directed upwards against the intrados of a stone arch—the direction of all others in which the voussoirs are most easily dislocated. This action can only be resisted by very careful workmanship in the dressing and setting of the *backing.* Another objection, applicable to all except tideless seas, such as the Mediterranean, arises

from the varying level of the surface of the water; for what may be best at one time of the tide, for one part of the curved wall, cannot be equally suitable at another.

*Treacherous Nature of Clay as a Foundation—Ardentallan Pier.*—A special caution regarding clayey bottoms may not be out of place here. Many are apt to suppose that there can be no better foundation than clay; and it is indeed true that some kinds of hard clay form a very satisfactory subsoil. But there are others of softer consistency, and permeated by sandy beds, which are extremely treacherous. Ardentallan Pier (Fig. 26) was erected in Loch Feochan, near Oban, in 1838, and was used for the export of stone from a quarry, of

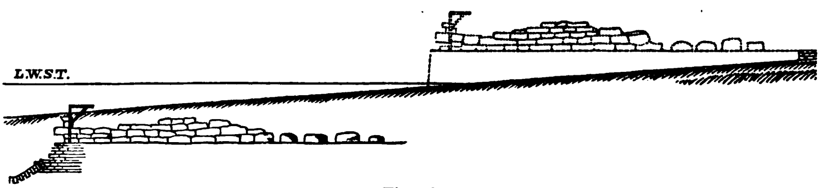



Fig. 26.

the same name, immediately adjacent. The beach, at the place, sloped at the rate of about 1 in 6, its surface being coarse gravel mixed with clay and sand, which presented the appearance of a foundation of the firmest and most substantial character. Below low water the bottom dipped at the rate of about 1 in 12½. So satisfactory did the ground appear that the walls were founded on the surface without any excavation being made. The quay or breast-wall forming the outer end of the pier was 120 feet in length of face, and was founded at the level of about a foot below low water. The hearting consisted of quarry rubbish and *terring*,[1] the length of quay, measured seawards from high-water mark, was 180 feet, and

[1] Terring, from the Latin *terra*, earth, is the Scotch term for the soil removed in clearing the top of a quarry.

it was 6 feet thick and 12 feet high, with a face batter on that height of 9 inches. In 1838 there were upwards of 200 tons of dressed stone deposited on the pier, and at that time it showed no symptoms of failure. In January 1844, however, while there were only 120 tons of material on the pier, the crane, which was on the outer end, suddenly began to move and shake; transverse openings across the roadway also appeared, which soon got wider. The workmen, in much alarm, sent for the foreman from the quarry, who on his arrival saw, to his great consternation, the whole mass rapidly sinking and moving seawards, excepting about 4 feet at the land end, which remained firm. The quay at the outer end soon slid out at the bottom so as to incline at an angle of about 45°. In this way the whole pier, with the dressed stones on its top, rapidly slid outwards and downwards, and, within *two hours* from the first indication of motion, no part of the pier or even the crane could be seen; and, on sounding, it was found that the top of the quay was more than 23 feet below low water. The *horizontal* movement was 150 feet in two hours, or at the rate of about 15 inches horizontally per minute, while in the same time the *vertical* movement was 34 feet, being 3.4 inches per minute. I ascertained these facts on visiting the ground after the accident, while the edges of the deep chasm which had been left were still fresh and unaltered. The clay forming the beach appeared to have resulted from the decomposition of the adjoining clay-slate rocks, and under the surface it was of a soft and almost semifluid consistency, and arranged in thin layers or films *parallel to the slope of the beach near high water, but dipping more quickly near low water.* The different layers of clay, which varied in thickness from about one quarter to only about one-fiftieth of an inch, were separated from each other by thin films of sand. The layer of coarse gravel, which

formed the hard surface on which the pier was founded, was only about 6 inches thick. The cause of failure seems to have been the slipping of some of the lower clay-beds, probably at one of the sandy seams, for I know of another case in which a clay-bank slipped forward on a similar thin sandy film. This accident shows the propriety of testing the subsoil by boring or sinking trial pits, and the danger of resting satisfied merely with superficial appearances. It also proves the treacherous nature of stratified clay when associated with films of sand. Another somewhat similar case will be found under the next section relating to timber piers and quays.

*Application of foregoing Principles to the Erection of a Building on a Sandbank.*—This chapter may perhaps be best recapitulated by applying the principles it lays down to a case of known difficulty, viz. the erection of a building on a sandbank—such, for example, as the erection of a lighthouse on the Goodwin Sands. The reader may not perhaps have forgotten the disinterested attempts to erect "the light of all nations," as it was called, as well as the many chimerical projects for effecting the same object, in all of which ingenuity was far more conspicuous than practical judgment. The difficulties, as I have elsewhere shown, which have in such a work to be contended against, are principally the *reaction of the waves from the building upon the soft bottom;* and the mistake which was committed, in all the designs for erecting a tower on this quicksand, was in adopting the principle of *mechanical fixture* in preference to that of *dead weight.* Without abandoning the known and fully-tried principles of marine engineering, the object, if it be one—for I express no opinion on that point—could be easily and certainly accomplished by simply depositing rubble stones in the sea, and allowing them to assume their own slope; and thus, after

a few years of labour, ultimately to form a small island of *pierres perdues,* similar to what was proposed in America, in 1835, for Delaware Bay. In this operation there is neither novelty nor difficulty, nor any room for doubt as to success. This will appear by collecting together the requirements for such a work: (1) Pliancy of the mass of materials employed, so as to admit of this artificial island adapting itself without dismemberment to the changes of form consequent upon unequal settlement. (2) That the structure shall rise out of the sand at a low angle, so as to reduce to a minimum the reaction upon the quicksand. (3) That that part of the structure where reaction must to some extent occur shall be far distant from the place where the tower is to be erected. (4) That the connection of the structure with the bottom shall not depend upon mechanical fixtures. (5) That if any partial damage takes place during the erection, the ruins shall act as a check to farther encroachment. (6) That the waves shall not impinge with full force upon the tower itself, but shall be broken before they reach it.

*Exposed Sandy Coasts.*—A difficulty of this kind was found at Arklow Harbour, and in order to protect the work trenches were excavated below the level of the foundations, and afterwards filled up with rubble, and also with concrete *in situ.* Another mode was adopted at Hynish by using long stones for a talus wall, the stones being set on dipping beds, and when the sandy bottom was underwashed by a gale, the stones forming the face of the wall sank till they came to nearly level beds without occasioning any dislocation of the masonry. When the wall was being built it settled bodily after on-shore gales, sometimes to a considerable extent.

# CHAPTER VIII.

## DESIGN OF GROUND-PLAN OF HARBOURS.

General Rules—Entrance at Seaward part of Works, and coincident with direction of heaviest Waves—Width of Entrance—Direction of Piers and Winds—Travelling Shingle—Good "Loose"—Curved and Straight Piers—Free and Confined Waves—Outer Basins—Ratio of Entrance to Area—Tranquillity of a Harbour not always proportional to its calculated Reductive Power—Direct Exposure not always proportional to Length of Fetch—Protective Value of a Breakwater—Lengthening a Breakwater may increase Sea—Reduction of Waves by Lateral Deflection—Breakwaters shelter Uninclosed Roadsteads—Reduction under lee of Piers with free ends—Reduction in close Harbours—Formula for Reductive Power—Cellular Structure for reducing Waves—Stilling Basin—Situations for unprotected Quays—Booms—Capacity of Commercial and of Fishing Harbours—Small Harbours more difficult to design than Large ones.

IN laying out the general design or ground-plan of a harbour, the principal matters to be kept in view are the proper disposition of the lines of the piers, so as to insure safe and easy ingress and egress, and the inclosure and protection of a sheet of water of sufficient depth.

The positions in which the piers of a harbour are to be placed depend on the nature and configuration of the shore and of the bottom. Before any step can be taken, the engineer must have before him numerous and accurate soundings, so as to give a correct representation of the bottom. The means of obtaining such data come strictly within the range of marine surveying, and I will not therefore enter at all upon the subject of these preliminary investigations, but shall leave the

reader to consult those works which are specially devoted to this branch of surveying.[1]

After a correct plan, with soundings, has been obtained, the next step is to lay down contour lines of the different depths, which make the limits of the deep and shoal water at once obvious to the eye. The lines of the piers may then be sketched, so as, without disregarding other conditions, to keep the works as much as possible on the shoal ground, while they at the same time inclose the greatest possible area of deep water.

*General Rules for designing Harbours.*—Many points requiring great care, for they affect vitally the ultimate success of the whole scheme, now present themselves for particular study. Among the most prominent of these—for we cannot take cognisance of all the peculiarities and the difficulties which may be found in every locality—are the following:—

1. *Entrance always at Seaward part of Works.*—The entrance should be fixed *seaward* of every other part of the works. If it be placed landwards, or even in line with a pier, we may cause an accumulated wave to be formed, which will pass into the harbour, or run across its mouth, rendering vessels unmanageable at the critical moment of "taking the port."

2. *Direction of the Entrance should, when possible, coincide with that of the Heaviest Waves.*—Unless where the internal area is small, and the sea very heavy, the direction of the entrance should be made to coincide with the direction of the heaviest waves, so that they may run along with, and guide vessels into the harbour. It is, no doubt, a simple and very efficacious mode of increasing the reductive power of a harbour to place the entrance at right angles to the line of movement of the swell. The old harbour of Pulteneytown furnishes a notable

[1] *Vide* D. Stevenson's "Marine Surveying." Edinburgh, 1842.

example of this disadvantageous arrangement. Such an expedient should indeed never be resorted to if it can possibly be avoided; for when a vessel *takes* a port having an indirect entrance of this sort, she is liable to be struck by the waves on her broadside or quarter, at the moment of turning in, and she thus runs a great risk of missing the harbour altogether and being stranded. If there be plenty of sea-room, this danger may be obviated by extending the outer pier sufficiently far seaward of the end of the other pier-head, so as to give it what we have called a free end, as in Fig. 27, and thus to allow a

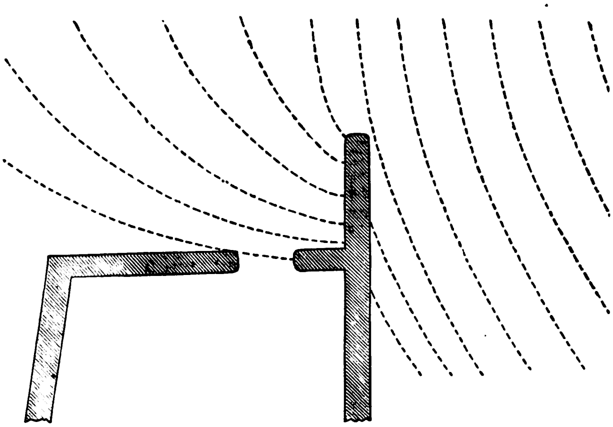


Fig. 27.

ship plenty of sea-room to shape an easy course. Even if, while rounding in, she should be struck by a wave so as to make lee-way, there is still sufficient time for her to recover herself under shelter of the outer breakwater before reaching the narrow entrance between the piers.

3. *Width of Entrance.*—The width of entrance channel varies from about 100 to 400 feet and upwards. The following Table, compiled from various sources, gives the width of entrance of different ports :—

| | Feet. | | Feet. |
|---|---|---|---|
| Helvoetsluys (Minard) | 108 | Leith | 240 |
| Seaham (Admiralty Chart) | 115 | Yarmouth (J. Walker) | 250 |
| Dover (Chart) Old Harbour | 150 | Gravelines | 305 |
| Newhaven (Admiralty Pilot) | 150 | Sunderland | 270 and 368 |
| Donaghadee (Chart) | 150 | Do. South | 230 |
| New Shoreham | 176 | Howth | 315 |
| Ramsgate | 190 | Calais (Channel Pilot) | 263 |
| Portland (Small Entrance) | 400 | Penzance | 330 |
| Ostende (Minard) | 360 | Aberdeen | 378 and 1100 |
| Port Rush | 210 | Flushing (Minard) | 426 |
| Ayr | 300 | Portsmouth | 750 |
| Boulogne | 200 | Kingstown | 750 |
| Dunkirk | 207 | | |

4. *Direction of Piers and Prevalent Winds.*—The piers should be laid out with reference to the direction of the prevalent wind. Minard says that at Bayonne, where they make an angle of 12° with the prevalent wind, they have been found to suit best the wants of the mariner.

5. *Danger of Travelling Shingle.*—If the beach consist of travelling detritus, the entrance must be so devised as not to form a trap for the passing shingle. This danger is most to be dreaded on the coasts where heavy waves strike obliquely upon a gravelly shore.

6. *Importance of a good "Loose" or Point of Departure.*—There must be a good "loose," so that vessels on leaving the harbour shall be able to shape their course free of rocks or a lee-shore; but as Minard very properly remarks, the mouths of harbours should be designed rather to suit the entrance than the exit, as vessels safely sheltered within the harbour may wait for favourable conditions for departure.[1]

The following digest of 266 wrecks and casualties, occurring from different causes, is taken from the Harbour of Refuge Commission Report of 1859 :—

[1] *Ouvrages Hydrauliques*, p. 31.

| | | |
|---|---|---|
| Abandoned at sea from various causes | | 7 |
| Burnt (fire caused by a cargo of lime getting wet) | | 1 |
| Capsized | | 4 |
| Damaged on piers or bars through insufficiency of tugs or tow-ropes | | 13 |
| Explosions from coal gas generated under hatches | | 4 |
| Foundered at sea and at anchors from various causes | | 36 |
| Leaky or dismasted and otherwise crippled (put back to repair) | | 22 |
| Stranded or struck on rocks, bars, and piers, *in entering or leaving ports and harbours*, viz.— | | |
| Blyth | 1 | |
| Hartlepool | 12 | |
| Hauxley | 1 | |
| Hird Sand | 5 | |
| Seaham | 3 | |
| Scarborough | 3 | |
| Shields | 3 | |
| Sunderland | 27 | |
| Whitby | 3 | |
| | — | 58 |
| Stranded or struck on rocks and sands from various causes | | 119 |
| Struck on sunken wreck | | 2 |
| Total | | 266 |

This table shows that more than one-fifth of the whole casualties, occurring within the period mentioned, took place in entering or leaving port, and if to this we add those damaged on piers or bars through insufficiency of tow-ropes, we shall have upwards of one-fourth of the whole; or, in other words, the table shows that the mariner has often to encounter his greatest perils when he is nearest to his port of destination or departure.

7. *Piers of Horizontal Curvature preferable to Long Straight Piers.*—Preference should generally be given to a pier of horizontal convex outline, or of a polygonal form, rather than

to one long straight pier running at right angles to the worst waves. The principal objection to a straight pier does not, however, extend to cases where the heaviest waves strike upon it obliquely, and roll landwards along the sea-wall.

8. *Free Waves and Confined or Gorged Waves.*—Especial care, however, must in all cases be taken, that a pier nowhere presents to the sea a surface of *concave horizontal outline*, or, what is still worse, abrupt faces which form a re-entrant angle; as the waves will then act with an almost explosive violence. For the breaking of a free wave is a very different thing from the breaking of a wave confined by a barrier of masonry. While the first may be compared to the harmless ignition of a loose heap of gunpowder, the other resembles the dangerous explosion produced by the discharge of a cannon.

It may, in some cases, be found better, in designing a *sea-wall* for protecting a sinuous coast, to carry the bulwark straight across ledges of rock which extend landwards, than to follow the line of the high-water margin. For although, with the straight wall, we have to encounter a greater depth of water and a heavier surf, still with the other we may have to oppose the waves with a wall which has at some places a concave horizontal curve, by which the force is concentrated and rendered far more destructive. Moreover, the straight wall may be considerably shorter than the curved.

9. *Outer Harbour or Stilling Basin.*—There should be sufficient distance landward of the mouth to allow a vessel, having full weigh on her, to shorten sail. For this Sganzin allows a distance of not less than two cables' lengths, and Minard recommends from 200 to 300 metres (1000 feet). Where the vessel requires to alter her course in order to reach the inner basin, no circle with a less radius than 200 yards in

smooth water should, I think, if possible, be adopted for the ordinary class of coasting steamers.

10. *The Relation of Width of Entrance to Area of Harbour.*—The internal area should bear such a relation to the width of entrance as to produce a sufficient degree of tranquillity, called the *reductive power of the harbour,* for which directions will be hereafter given.

11. *The Tranquillity of a Harbour is not always proportional to its calculated Reductive Power.*—The dimensions of a harbour must be proportional to the height of wave to which it is to be exposed. If the basin be on so small a scale as not to afford sufficient space to give the waves time to sink freely after they have entered, the calculated will not agree with the observed results. The formula assumes that the waves after being reduced by lateral expansion shall have time to sink and be afterwards destroyed. But if instead of this they are reflected back again towards the entrance, such returned waves will destroy the tranquillity of the basin, and prevent vessels from answering their helms when taking the entrance. A harbour of the same reductive power which is suitable for a more sheltered locality may not therefore answer for a place that is less sheltered, unless it be made on a larger scale. Also when a spending beach, which is only partially effective, is formed very near the entrance, it may do more harm than good by causing a back-rush which will injuriously affect vessels when entering.

12. *The Direct Exposure of a Harbour is not always proportional to the length of fetch measured in the line of the Entrance Channel, and extended till it meets the nearest Land.*—The waves which enter directly the harbour mouth in a case such as shown in Fig. 28, though apparently generated in the fetch AB, are largely due to the fetch BC. For the waves

generated in the length CA pass round the point A and are thereafter subject to the wind passing along AB. The waves then which enter the harbour mouth directly, instead of having

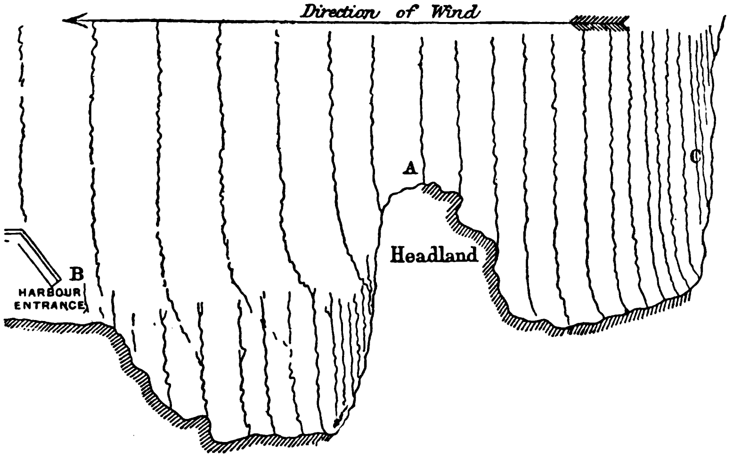



Fig. 28.

their origin or place of genesis at A, really take their origin at C, though their height is to some extent reduced by deflection round the point A.

13. *Protective Value of a Breakwater is Proportional to the Resistances which it overcomes.*—The amount of protection which is produced by a breakwater must be measured by the length of the portion of the wave which is either destroyed or reflected by it. The amount of work done by it decreases from the maximum which is at normal incidence to the minimum when the waves come upon it *end on,* in which last case no work is done, and it ceases to act as a breakwater for waves coming in that direction, excepting to the small extent due to lateral erosion.

14. *Lengthening a Breakwater may increase the Sea within*

*the Harbour, instead of reducing it.*—If a breakwater be so placed in relation to the coast-line that waves can strike upon its inner or landward side; an extension of its length in the same direction will increase the amount of sea intercepted by it. In this case the extension must be made in an altered direction, or a separate breakwater must be built so as to shelter the inner side, or else an additional sheltered space of water or of the shore must be provided, in which the waves can spread or be expended.

### Reduction of Waves by Lateral Deflection.

*Effects of Breakwaters in sheltering uninclosed Roadsteads.*—No general remarks, that could prove of the slightest use in any particular case, can be made regarding some of the provisions which have been mentioned, but there are others of a more definite nature, and depending less on local peculiarities, which admit of further elucidation. Among these—and it is one of the most important—is the manner of estimating the reduction of the waves when they are deflected from their original direction and made to diverge into sheltered water. And I cannot but express regret that no attempt has been made, so far as I am aware, to obtain exact numerical results on this point, derived either from theory or experiment. I have been unable, indeed, to find that a single observation or experiment of any kind has been made upon the subject, and yet the whole benefits which are expected to result from the erection of our great national breakwaters depend entirely upon the reduction of the waves. When a wave encounters an obstacle such as a breakwater, the portion which strikes it is either entirely destroyed or is reflected seawards, while the portion which is not so intercepted passes onwards, and, spreading laterally under lee of the barrier, suffers a reduction of its

height. It is this reduction of height which it is so desirable to determine; and I hope that those who have opportunities of making observations on the effects of breakwaters in sheltering uninclosed roadsteads will be induced to take up the subject, which is undoubtedly one of great importance. My son, Mr. Robert Louis Stevenson, made some observations at angles of 45° and 90° at Pulteneytown breakwater, and these gave a coefficient of about .06 for the formula given in the next article, which, *for the class of waves observed,* would in this case be—

$$x = 1 - .06 \sqrt{a^\circ}$$

where $x$ represents the ratio of the reduced to the unreduced wave, and $a$ the angle of deflection.

*Reduction of Waves immediately under Lee of Piers with Free Ends.*—When the waves are deflected behind a pier with a free end, and run along its inner side, the reduction which they suffer will be due to the distance passed over, and to the angle of deviation produced by the pier. Though far from placing reliance on so slender a stock of facts as I am in possession of, and which were partly the result of observations at sea, and of experiments made in a brewer's cooling tank about four or five inches deep, I may just mention that the amount of *reduction* in the height of an unbroken wave, after being deflected, was found to increase *directly as the distance traversed, and as the square root of the number of degrees in the angle of deflection.* The following unconfirmed formula represents the results with the class of waves which were observed at different harbours, but it is given simply as a possible approximation, and it is obvious that the coefficient must, as in the former case, be variable, depending on the kind of wave :—

$$x = 1 - .04 \sqrt{a^\circ}$$

in which $x$ represents the ratio of the reduced to the unreduced wave, and $a$ the angle of deflection.

In the subjoined table are given the heights observed at the harbour of Latheronwheel:—

| 1858, Original height of Wave. | Distance passed over. | Angles. | Results by Formula. | Observed Reduced Heights. |
|---|---|---|---|---|
| 4.5 ft. | 16 ft. | 51° | 3.2 ft. | 3.0 ft. |
| 5.0 ,, | ,, | ,, | 3.6 ,, | 3.5 ,, |
| 4.5 ,, | ,, | ,, | 3.2 ,, | 3.0 ,, |
| 6.5 ,, | ,, | ,, | 4.6 ,, | 5.0 ,, |
| 3.0 ,, | ,, | 90° | 1.9 ,, | 2.0 ,, |
| 3.5 ,, | ,, | ,, | 2.2 ,, | 2.5 ,, |
| 4.0 ,, | ,, | ,, | 2.5 ,, | 2.5 ,, |
| 5.0 ,, | ,, | ,, | 3.1 ,, | 3.0 ,, |
| 4.5 ,, | 32 ft. | 140° | 2.4 ,, | 2.0 ,, |
| 5.0 ,, | ,, | ,, | 2.6 ,, | 2.5 ,, |
| 4.5 ,, | ,, | ,, | 2.4 ,, | 2.5 ,, |
| 6.5 ,, | ,, | ,, | 3.4 ,, | 3.0 ,, |

These observations were made at the outer kants of the pier of Latheronwheel, which is single, with a free end, and which acts on the waves in a different manner from a harbour which forms an *inclosed* area, to which I shall next refer.

## Reduction in the Height of Waves after passing into Close Harbours.

The ultimate object of every harbour is to preserve the tranquillity of the inclosed area by lowering the height of the waves as they enter, and this property is variously possessed by harbours of different forms, and depends upon the relative widths of the entrance and the interior, the depth of water, the form of the entrance, and the relation between the direction of the entrance and that of the line of *maximum exposure.*

*Formula for Reductive Power.*—The only formula with which I am acquainted which gives the *reductive power* of a close harbour, is that which I published in the *Edin. Phil. Journal* for 1853. When the piers are high enough to screen the inner area from the wind, where the depth is tolerably uniform, the width of entrance not very great in comparison with the section of the wave, and when the quay-walls are vertical, or nearly so, and the distance not less than 50 feet from the mouth of the harbour to the place of observation, the following formula is applicable—

$H$ = height of wave at entrance, in feet;
$b$ = breadth of entrance, in feet;
$B$ = breadth of harbour at place of observation, in feet; or more accurately, length of the arc with radius $D$;
$D$ = distance from mouth of harbour to place of observation, in feet;
$x$ = height of reduced or residual wave at place of observation, in feet.

$$x = H\frac{\sqrt{b}}{\sqrt{B}} - \frac{\left(H + H\frac{\sqrt{b}}{\sqrt{B}}\right)\sqrt[4]{D}}{50}.$$

If $H$ be regarded as unity, $x$ will come out a fraction which will represent what we may call the *reductive power* of the harbour at the point for which the calculation has been made; and by multiplying the height of any wave at the entrance by the fraction $x$, its reduced height is found.[1]

This formula is founded partly on the conclusions arrived

[1] In the *Encyclopædia Britannica* the formula was stated in perhaps a better form, viz.—

$$x = H\left\{\sqrt{\frac{b}{B}} - \frac{1}{50}\left(1 + \sqrt{\frac{b}{B}}\right)\sqrt[4]{D}\right\}$$

but that given above is more convenient for calculation.

at by Dr. Thomas Young, in 1807, in his theory of undulation, and partly on observations. These observations included the determination of the centres from which the waves expanded, and which appear to be situated not far from the middle of the entrance.

The method of applying the formula is to describe a circle on the ground-plan of the harbour from the point of union of the lines of the piers produced seawards, or (what is sufficiently near) from the middle point of the entrance. The radius adopted must be equal to the distance (D) between the centre of divergence and the place on the pier where the reductive power is wanted. The arc of a circle thus described must extend so far as to intersect the two side walls of the harbour, or, in cases where one of the piers meets the shore at a shorter distance, the arc must be extended to the line of direction of the shorter pier produced landward of the high-water line. It is necessary to observe, however, that in such cases as the last named, where the shore intervenes, the formula is not applicable unless the beach slopes sufficiently to allow the waves to spend themselves freely. The distance B is then measured as a chord between the two points of intersection ; or where the versed sine is large, B should be taken equal to the length of the arc. It is believed that this formula will be found to be of general application in all close harbours where the entrance is of a direct and simple nature, and in which there is no recoil action produced by walls or obstructions to the *shoreward* motion of the waves.

In order to show the correspondence between the actual observations and the results of calculation by the formula, a table is subjoined, which contains averages of the observations at the different places mentioned. Those at Buckie are reduced from upwards of 2000 observations.

## RESULTS of FORMULA for REDUCTIVE POWER of HARBOURS, compared with Observations.

| Name of Harbour. | Calculated Reductive Power. | Observed Reductive Power. | Height of Wave in Interior of Harbour. A. By Calculation. | B. By Observation. | Remarks. |
|---|---|---|---|---|---|
| Kingstown . . . | .307 | .374 | 2¼ ft. to 3 ft. | 3 ft. to 3¾ ft. | |
| **Sunderland.** | | | | | |
| 1st. At stair on South Pier, at entrance to beaching ground . . | .440 | .385 | 5.72 feet. | 5.00 feet. | |
| 2d. At South Dock . . | .1015 | .1023 | 1.32 ,, | 1.33 ,, | |
| **Macduff.** | | | | | |
| 1st. 165 feet from inner entrance . . . | .44 | .60 | 1.10 ,, | 1.50 ,, | |
| 2d. 340 feet from inner entrance . . . | .42 | .532 | 1.05 ,, | 1.33 ,, | |
| **Fisherrow.** | | | | | |
| 1st. On west side . . | .478 | .472 | 2.39 ,, | 2.36 ,, | |
| 2d. On east side . . | .430 | .384 | 2.15 ,, | 1.92 ,, | |
| **Buckie.** | | | | | |
| 1st point of observation . | .649 | .534 | 6.17 ,, | 5.07 ,, | Mean of 244—*a.* |
| ,, ,, | ,, | .533 | ,, ,, | 5.06 ,, | Mean of 117—*b.* |
| ,, ,, | ,, | .534 | ,, ,, | 5.07 ,, | Mean of 127—*c.* |
| ,, ,, | ,, | .570 | ,, ,, | 5.41 ,, | Results of storm, Nov. 1857—*d.* |
| 2d point of observation . | .464 | .323 | 4.41 ,, | 3.07 ,, | *a*, as above. |
| ,, ,, | ,, | .338 | ,, ,, | 3.21 ,, | *b*, ,, |
| ,, ,, | ,, | .309 | ,, ,, | 2.94 ,, | *c*, ,, |
| ,, ,, | ,, | .394 | ,, ,, | 3.74 ,, | *d*, ,, |
| 3d point of observation . | .233 | .207 | 2.20 ,, | 1.97 ,, | *a*, ,, |
| ,, ,, | ,, | .229 | ,, ,, | 2.18 ,, | *b*, ,, |
| ,, ,, | ,, | .186 | ,, ,, | 1.77 ,, | *c*, ,, |
| ,, ,, | ,, | .342 | ,, ,, | 3.25 ,, | *d*, ,, |
| 4th point of observation | .186 | .157 | 1.77 ,, | 1.49 ,, | *a*, ,, |
| ,, ,, | ,, | .183 | ,, ,, | 1.74 ,, | *b*, ,, |
| ,, ,, | ,, | .134 | ,, ,, | 1.27 ,, | *c*, ,, |
| ,, ,, | ,, | .289 | ,, ,, | 2.75 ,, | *d*, ,, |
| 5th point of observation | .143 | .136 | 1.36 ,, | 1.29 ,, | *a*, ,, |
| ,, ,, | ,, | .162 | ,, ,, | 1.54 ,, | *b*, ,, |
| ,, ,, | ,, | .113 | ,, ,, | 1.07 ,, | *c*, ,, |
| ,, ,, | ,, | .158 | ,, ,, | 1.50 ,, | *d*, ,, |
| 6th point of observation | .119 | .139 | 1.13 ,, | 1.32 ,, | *a*, ,, |
| ,, ,, | ,, | .160 | ,, ,, | 1.52 ,, | *b*, ,, |
| ,, ,, | ,, | .120 | ,, ,, | 1.14 ,, | *c*, ,, |
| ,, ,, | ,, | .175 | ,, ,, | 1.66 ,, | *d*, ,, |
| 7th point of observation | .209 | .222 | 1.99 ,, | 2.11 ,, | *c*, ,, |
| ,, ,, | ,, | .289 | ,, ,, | 2.75 ,, | *d*, ,, |
| 8th point of observation | .274 | .232 | 2.60 ,, | 2.20 ,, | *c*, ,, |
| ,, ,, | ,, | .368 | ,, ,, | 3.50 ,, | *d*, ,, |
| 9th point of observation | .427 | .339 | 4.06 ,, | 3.22 ,, | *c*, ,, |
| ,, ,, | ,, | .491 | ,, ,, | 4.66 ,, | *d*, ,, |

Mean of *all* the *calculated* heights in column A . . . . . . . 2.64 feet.
Mean of *all* the *observed* heights in column B . . . . . . . . 2.62 ,,
Mean of the *observed* heights, taking under Buckie only those marked *a*, and those marked *c* where *a* is wanting (at points 7, 8, and 9) . . 2.47 ,,
Mean of *observed* heights in B, taking only those marked *c*, under Buckie 2.41 ,,

*Side Channels for reducing Waves.*—At the harbour of West Hartlepool an ingenious and novel device for reducing the height of the waves has been carried out by Mr. R. Ward Jackson and Mr. Casebourne. Interior expansions have been made to communicate with narrow canals running landwards, and which ultimately join the sea outside of the harbour. The portion of the wave which has been detached by spreading into the lateral channels is thus conducted entirely out of the harbour into the open sea. At Mullaghmore, County Sligo, where the *run* was troublesome in stormy weather, the basin has, I am informed, been much smoothed by an opening made at the upper end of the harbour, through which the swell passes out to the beach, instead of being reflected by the inner walls.

*Cellular Structure for Reducing Waves; "clair voie."*—There are many places so narrow and confined by rocks as not to admit of the formation of lateral expansions either of the usual kind or of that adopted at Hartlepool. In such situations some reduction might, I think, be effected by converting the upper portion of the quay-walls at and near the entrance into a series of chambers, separated from each other by *vertical* diaphragms, so as to smooth the water by forming numerous *stops*. This cellular structure, in some respects similar to what is called in France "*clair voie*" (which is found to answer best with $\frac{1}{3}$ of solid to $\frac{2}{3}$ of void), might be cheaply constructed of vertical partitions of timber. The action of the cells consists in abstracting from the upper part of the wave a small portion of water, and retaining it momentarily until the crest has passed the mouth of the cell, when the water so retained falls again into the harbour on the *back* of the wave from which it had been abstracted. If the entrance-passage were of some length, even although the openings were

of small width, a considerable reduction would be produced by this repeated process of separation and detention. The tranquillising tendency of such *stops* may, to some extent, be estimated by noticing the action on a passing wave of vertical fenders on the face of a pier. On a somewhat similar principle the waves are sometimes reduced by making a portion of the outer piers of *open* timber work, which allows the wave to burst through it.

*Stilling Basin.*—As before mentioned, it is essential when the exposure is great, that there be either a considerable internal area, or else a separate basin outside the entrance to the inner basin, for the waves to destroy or *spend* themselves. Such a basin should, if possible, inclose a portion of the original shore for the waves to break upon, and when circumstances preclude this, there should be a flat talus wall of at least 3 or 4 to 1, as recommended by the late Mr. Bremner of Wick. Mr. Scott Russell has found that talus walls of 1 to 1, or steeper, will not allow the waves to break fully, but will reflect them in such a manner as might in some cases make the entrance difficult or even dangerous of access, and the berthage within unsafe; and I can corroborate this from personal observation. Instances are not wanting of harbours being materially injured by the erection of a vertical wall constructed across a sloping beach on which the waves were formerly allowed to expend their force. The experiments made by the committee of the British Association exemplify this. Small waves from one quarter to half an inch high, which were generated in a box 20 feet long, could be traced after being reflected 60 times, and after having passed over a space of 1200 feet.

*Situations where unprotected Quays may be used.*—The following cases, in which traffic has been successfully carried

on at quays unprotected by covering piers, may be found useful as a guide:—

At Scrabster the quay is at right angles to a fetch of 6 miles.
At Invergordon there is a fetch of 5 miles.

| | | | |
|---|---|---|---|
| At Burntisland | „ | 6 | „ |
| At Kilcreggan | „ | 4 | „ |
| Londonderry | „ | 1½ | „ |
| Greenock | „ | 6½ | „ |
| Albert Quay, Greenock | „ | 7 | „ |

The two last are, however, somewhat sheltered at low-water by the low-water banks near Greenock.

So far as my experience goes, I think that 5 miles is probably not far from the limits that should be observed, which by the ordinary formula, $h = 1.5 \sqrt{D}$, gives a wave of 3.3 feet; but the formula for distances so short as these would give waves about a foot higher, and in heavy storms perhaps waves not much less than 5 feet may exist, but on such occasions vessels could not safely use the quay.

*Open Timber Wharves useful for preventing Waves from being reflected.*—Waves, when not of large size, can often be either *destroyed* or prevented from being reflected by adopting a sloping face of stones, with open timber quay in front.

*Booms for excluding Waves.*—In order to tranquillise harbours of small reductive power, logs of timber, called booms, having their ends secured into grooves cut in the masonry on each side, are placed across the entrance of the inner basin or dock. From 10 to 20 logs are usually dropped into those grooves, or as many more as will insure close contact of the lowest log with a sill-piece placed in the bottom of the harbour. They are also warped down or fixed

with an iron hasp at the coping course, without which precaution the swell is found to enter the harbour from underneath. By this contrivance, which forms a temporary wall, the waves are checked, and completely prevented from spreading into the interior basin. The longest booms I have seen are at Banff, where the span is 43 feet; and in some places, as at Hartlepool and Seaham, in Durhamshire, they are taken out and in by steam-power. Twelve-inch booms of pine timber, about 33 feet long, have been broken at the small fishing village of Mousehole, near Penzance, and elm logs have in consequence been substituted. At Hynish, in Argyllshire, booms of the same timber and scantling, and 20 feet long, have, as already stated, been very frequently broken.

Though booms are perfectly successful in their tranquillising effect (provided they are kept in contact with the sill-piece at the bottom), yet they are not suited for harbours where there is much traffic, as the "*shipping*" and "*unshipping*" of so many logs of timber involve a delay which might be attended with serious consequences, though this risk may be materially reduced by the employment of hydraulic power. Hollow booms constructed of boiler-plate, on the tubular bridge principle, might be found suitable for large spans; and if their buoyancy were destroyed by making them pervious to water, they would not require to be warped down, as is necessary when logs are used.

*Capacity of Harbours for Commerce.*—The capacity of commercial harbours for trade varies so much with the exposure and size of vessels, that it is difficult to approximate to the truth. At Ramsgate, for instance, there were found to be about 6 vessels to an acre in the outer harbour, while there were about 14 in the inner and better protected basin, where too there was perhaps a greater proportion of small vessels.

*Capacity of Fishing Harbours.*—In the Scotch fishing harbours the number of boats used to be reckoned at from 85 to 115 per acre; but of late their size has been much increased, and probably not more than from 40 to 50 could be accommodated. The Cornish boats at New Lynn, according to the Channel Pilot, vary from 60 to 80 per acre.

*Small Harbours, in some respects, more difficult to design than Large Ones.*—I cannot leave this part of the subject without observing that, in some particulars, the difficulties of design are inversely proportional to the extent of the works. Indeed, if the piers inclose a very large area, some of the elements of difficulty nearly altogether disappear. Little attention need then be given to those questions which are so troublesome in small basins regarding reductive power, want of spend, and recoil of waves; and comparatively little as to the width of the entrance.

# CHAPTER IX.

## DOCKS, TIDE-BASINS, LOCKS, GRAVING-DOCKS, SLIPS, ETC.

**Advantages of Docks—Entrances to Docks and Slips—Outer or Tide Basins—Proportions of Outer Basins to Dock Areas—Locks—Lockage—Dimensions of Docks—Dock of Maximum Capacity—Available Capacity of Quays—Proportions of Quay per Acre of Water Space—Docks should be sheltered from Wind—Capacity of Docks: Amount of work done at—Graving Docks—Iron Floating Docks—Hydraulic Lift—Patent Slips—Gridirons—Hydraulic and Screw Docks—Relative Advantages of Slips and Graving Docks—Shipbuilding Stances—Dock-gates—Caissons—Dock Walls.**

ON applying our formula (p. 165) to any design for a harbour, we shall soon find whether it be possible to secure a sufficient amount of sheltered space within the piers. If the calculation shows that this cannot be done, the best course will be to divide the inclosed area into an outer and inner harbour; and if the reductive power even of the inner basin be still found too small, a dock or tide basin with gates may then be resorted to. But, in considering the eligibility of docks, we must also remember that the principal advantages they confer are the great conveniences for trade, which warrant their adoption in places where no protection from the waves is required.

*Advantages of Docks.*—The peculiar advantages afforded by docks are the following:—Vessels can be accommodated in the smallest possible space, and are enabled to lie constantly afloat; whereas in tidal harbours where they *take*

*the ground* they are apt to be strained or to have their floors broken. But there are other sources of mischief than this, for often, when the tide is ebbing, vessels, unless watched, fall against each other. In two instances, one of which gave rise to subsequent legal proceedings, where the bottom, which was muddy, had a considerable declivity, a ship, which had taken the ground on the beach near low-water mark, was actually run down and damaged by another stranded vessel, the warps of which suddenly snapped and freed her from the moorings at the quay, thus causing a collision between vessels, both of which were at the time high and dry. Then there is the chafing of the vessels' sides against the quays, and the breaking of warps during stormy weather, or during land floods where there is a river. It is said that at Sunderland damage to the extent of £40,000 was occasioned in one day by large quantities of ice that came down the Wear. When a vessel is in dock she can be easily and at all times moved from place to place, while the operation of discharging and loading can go regularly on during any time of tide. Her level, too, is never much affected, so that the cargo does not require to be hoisted so high as would otherwise be necessary. Timber vessels can be discharged through their ports into the water at all times of tide, while in harbours which are dry at low-water, the logs receive injury by falling on the hard bottom.

The relative eligibility of docks or tide basins depends much on the rise of the tide. In such rivers as the Clyde and the Foyle, where the lift does not exceed about 9 or 10 feet, docks are less needed than at the Mersey, Bristol Channel, and similar places, where the rise is from 30 to 40 feet.

*Entrances to Docks and Slips.* — Mr. Redman, who has

devoted much attention to the subject of the entrances to docks placed in a tideway, says "the practice in the port of London is to dock a ship upon the flood just before high water, and to undock her at about the same period of tide. . . . The directions apparently the most desirable are an angle of about 45°, pointing up the stream, for graving docks, and an angle of about 60° for wet docks."[1] Each case must, however, be judged on its own merits; as, for example, where there is a liability to the deposit of silt, it may be better that the entrance should point down stream.

*Outer or Tide Basins.*—The lock-gates through which vessels enter a dock are thrown open, as at Liverpool for example, for two hours before and one hour after high water, so that vessels can pass freely out and in. But as the tide falls they must be shut, otherwise the level of the water in the dock would be too much lowered. After that time of tide, vessels can only enter or leave by being locked up to the dock or locked down to the sea. Outer or half-tide basins, first introduced, it is believed, by the late Mr. Jesse Hartley, are formed between the lock and the river or sea, and admit of a large additional traffic being accommodated. The entrance to such basins is provided with sea gates, which are kept open till half-tide, or such other time of ebb as is found most suitable to the situation. Long after the lock-gates which form the entrance to the docks are closed, inward-bound vessels can run into the outer basin, and be afterwards passed into the docks; and in like manner outward-bound vessels can be passed down from the dock long after high water.

*The Proportions of Outer Basins to Dock Areas.*—The relative proportions of area of the outer basins to docks vary at different ports, according to the amount and nature of the

[1] *Min. Civ. Eng.* vol. xviii. p. 495.

traffic to be provided for. The following table shows the proportions at one or two harbours :—

PROPORTIONS of DOCK AREAS to AREAS of OUTER BASINS.

| | | Acres. | Ratio. |
|---|---|---|---|
| Bute Docks (East) Cardiff . | Basin<br>Dock | 2.15<br>42.33 | 1 : 20 |
| Do. (West) „ . | Basin<br>Dock | 1.244<br>16.86 | 1 : 13.5 |
| Penarth . . . . | Basin<br>Dock | 2.68<br>17.11 | 1 : 6.5 |
| Tyne . . . . . | Basin<br>Dock | 9.5<br>50.0 | 1 : 5.25 |
| Liverpool (General) . . | Basin<br>Docks | 13.0<br>107.0 | 1 : 8.23 |
| Royal Albert, Woolwich . | Dock<br>Basin | 75.0<br>9.0 | 1 : 8.4 |

*Locks.*—It is a curious fact, illustrative of the strength of prejudice, that, when Whitworth proposed to form a lock at Leith, in 1786, it met with strong opposition, on the ground of its being dangerous to shipping. Such an objection, it is almost needless to add, is never now heard of.

The dimensions of locks depend, of course, on the class of shipping that has to be provided for. In France the amount of *side-play* that is allowed for merchant vessels is generally .65 foot, and 1 foot for vessels of the first class. Minard allows from about 4 inches to about 10 inches between the sill and the vessel's keel. At Flushing he provided about $\frac{6}{10}$ foot for vessels drawing 24 feet; and he has seen ships of war pass through with only 6 inches under their keel. The following table shows the dimensions of some of the locks at different ports :—

TABLE.

| | Length of Lock. | | Breadth. | | Depth over Sill at High-water Springs. | |
|---|---|---|---|---|---|---|
| | Ft. | In. | Ft. | In. | Ft. | In. |
| Leith (Albert) . . | 350 | | 60 | | 26 | 6 |
| Dundee (Victoria) . . | 230 | | 60 | | 21 | 6 |
| Aberdeen (Victoria) . | 250 | | 60 | | 22 | |
| Dublin (Large Dock) . | 180 | | 36 | | 18 | |
| Cork . . . . . | 180 | | 45 | | 18 | 6 |
| Bristol (Cumberland) . | 266&350 | | 54&62 | | 32&35 | |
| Plymouth . . . | 250 | | 55 | | 24 | |
| Newport . . . | 220 | | 61 | | 31 | |
| Cardiff . . . | 350 | | 80 | | 35 | 8 |
| „ (Roath Dock) . | 600 | | 80 | | 38 | 8 |
| Swansea . . . | 160 | | 56 | | 23 | |
| Ipswich . . . | 150 | | 45 | | 16 | 6 |
| Hull (Humber) . . | 158 | 6 | 42 | | 26 | 6 |
| „ (Albert) . . | 320 | | 80 | | 28 | 5 |
| Great Grimsby . . | 300 | | 70 | | 25 | 6 |
| Goole (Railway) . . | 264 | | 58 | | 19 | 3 |
| Middlesborough (2 locks) | 132<br>132 | | 30<br>53 | | 18<br>22 | <br>3 |
| London (Victoria) . . | 350 | | 80 | | 28 | |
| „ (Albert) . . | 550 | | 80 | | 30 | |
| Avonmouth . . . | 454 | | 70 | | 38 | |
| Liverpool (Canada) . . | 498 | | 100 | | ... | |
| Tyne (Northumberland) . | 250 | | 52 | | 24 | |
| „ (Albert Edward) . | 350 | | 60 | | 36 | |

*Lockage.*—The late Dr. Rankine, in his *Manual of Civil Engineering*, gives the following table for the expenditure of water due to the passage of vessels through the lock :—

Let L denote a lockful of water, that is the volume contained in the lock chamber between the upper and lower water levels. B the volume displaced by a ship. Then the quantities of water discharged from the dock are shown in the table. The sign — prefixed to a quantity of water denotes that it is displaced from the lock into the dock.

| | Lock found | Water discharged. | Lock left |
|---|---|---|---|
| A descending ship . . | Empty . . | L − B | Empty. |
| „ „ . . | Full . . | − B | „ |
| An ascending ship . . | Empty or full | L + B | Full. |
| 2 $n$ ships descending and ascending alternately | Descending full<br>Ascending empty | $n$ L | Descending empty.<br>Ascending full. |
| Train of $n$ ships descending | Empty . . | $n$ L − $n$ B | Empty. |
| „ „ | Full . . | ($n$ − 1) L − $n$ B | Empty. |
| Train of $n$ ships ascending | Empty or full | $n$ L + $n$ B | Full. |
| Two trains of $n$ ships—the first descending, the second ascending | Full . . | (2 $n$ − 1) L | Full. |

From these calculations it appears that ships ascending and descending alternately, cause less expenditure of water than equal numbers of ships in train.[1]

## Side Play at Locks.

For barge locks *Smeaton* allowed 3″ on each side = 6″ in all.
*Brindley* „ 6″ „ = 12″ „
*Minard* „ $3\frac{1}{4}''$ to $3\frac{9}{10}''$ „ = $6\frac{4}{10}''$ to $7\frac{8}{10}''$ in all.
[2] *Whitworth* „ 6 „ = 12″ in all.

## Vertical Play at Locks.

For barge locks *Smeaton* allowed 1 inch over sill.
For barge *Canals vertical play*—
*Smeaton* „ 6 inches „
*Brindley* „ 6 „ „
*Chapman* „ 16 „ „[2]

[1] *Manual of Civil Engineering*, by W. J. M. Rankine. London, 1862, p. 751.
[2] *The Advantages of Inland Navigation*, R. Whitworth. London, 1766.

TABLE showing DIMENSIONS of different DOCKS.

| | Length in feet. | Breadth in feet. | Depth over Sill in feet. | | | |
|---|---|---|---|---|---|---|
| | | | Springs. | | Neaps. | |
| | | | Ft. | In. | Ft. | In. |
| Cardiff—West Bute | 4000 | 200 | 28 | 8 | 18 | 8 |
| ,, East Dock | 4300 | 300 to 500 | 31 | 8 | 21 | 8 |
| Penarth | 2100 | 370 | 35 | | 25 | |
| Bristol—Cumberland | 635 | 300 | 32 | | 16 | |
| Swansea | 1550 | ... | 23 | | 16 | |
| Newport | 1750 | 230 to 320 | 31 | | 22 | |
| Barrow—Devonshire | 2500 | ave. 250 | 25 | 6 | 18 | |
| ,, Buccleuch | 3000 | ave. 250 | 18 to 20 | | ... | |
| Garston | 1000 | 270 | 24 | | 15 | 6 |
| Avonmouth | 1400 | 500 | 38 | | 27 | |
| Grimsby | 2330 | 500 | 25 | 4 | 22 | 2 |
| Kingston—Hull | | | | | | |
| ,, Humber | 914 | 342 | 26 | 6 | 21 | |
| ,, Victoria | 1440 | 378 | 26 | 2 | 22 | |
| ,, Albert | 3350 | 200 to 430 | 28 | 5 | 23 | |
| ,, Queen's | 1703 | 254 | 20 | 8 | ... | |
| Plymouth—Mill Bay | 1260 | 450 | 31 | | 26½ | |
| London—Albert | 6600 | 490 | 30 | | ... | |
| Whitehaven | 570 | 340 | 21 | | ... | |
| Bo'ness | 840 | 280 to 430 | 20 to 22 | | ... | |
| Ayr | 550 | 500 | 23 | | 20 | |
| Clyde—Kingston | ave. 1110 | 200 | 22 | 6 | 20 | 6 |
| Ardrossan | 570 | 280 | 18 | 6 | 16 | |
| Leith—Albert | 1100 | 450 | 26 | 6 | ... | |
| ,, Edinburgh | 1500 | 650 jetty in centre 1000 feet long. | 26 | 6 | ... | |
| Belfast | 630 | 225 | 22 ? | | ... | |
| Tyne—Northumberland | 3700 | ave. 600 | 24 | | 20 | |
| ,, Albert Edward | 1300 | ave. 700 | 36 | | 32 | |

The docks at Liverpool have a total area of upwards of 324 acres, with a total quay space of more than 21 miles in length; while the area of the Birkhead docks is 159 acres, with a quay space of 9 miles.

*Dock of Maximum Accommodation for Trade.*—The general form of a dock will, in most cases, be dependent on local peculiarities. Where the nature of the ground and other circumstances admit of it, the width of the basin should, in order to provide for the largest amount of traffic, be greater at the entrance than at a distance from it. Fig. 29 is an

attempt to represent the form of maximum capacity for a dock, and although in most cases, owing to local circumstances, it may not be possible of adoption, yet it may be sometimes at least approximated to. Internal jetties with a

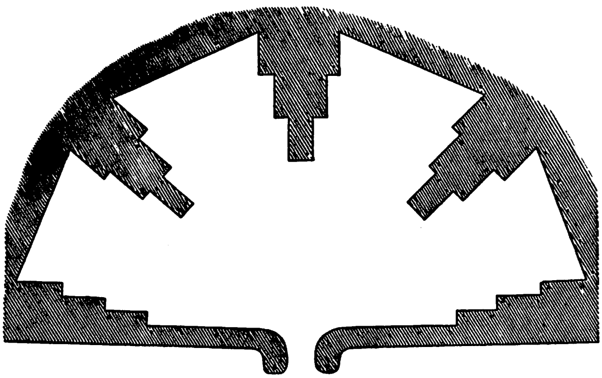


Fig. 29.

broken line of quay are in common use, but the radiating arrangement has not, so far as I know, been adopted. The object is to secure as much room as possible at and near the entrance.

*Available Capacity of Quays.*—The amount of work that can be done per yard-length of quay varies with the different facilities which are afforded for traffic, as, for example, whether common cranes or steam or hydraulic cranes are used, or whether there are ordinary carting or tramways connected with the shipping berths, or whether the depth of water in front is small or great, or whether the quay is exposed to the rise and fall of the tides as in a river, or whether the ships are always water-borne as in a dock. The available free space of ground behind a quay forms also an important element as regards traffic. Wherever possible, it is desirable to have at

least 100 feet of breadth behind the quay. At Glasgow there is generally allowed 115 feet of space. Vessels of 150 tons require about 100 feet of quay.

The following Table, given in Mr. Ure's report on the extension of Glasgow harbour in 1854, gives the amount of work done per annum, per yard of quay and per acre, at different ports :—

| | Tonnage per Acre of Water Space. | Tonnage per Lineal Yard of Quay. | Remarks. |
|---|---|---|---|
| Glasgow, including steamers | 30,670 | 440 | Fully worked. |
| ,, excluding ,, | 20,361 | 293 | |
| Southampton tidal harbour | 20,000 | 350 | Could do more. |
| Liverpool Docks . . | 21,200 | 185 | Fully worked. |
| St. Katharine's Docks . | 20,500 | 142 | ,, ,, |
| Hull Docks . . . | 19,000 | 143 | During nine months. |
| To this may be added the old Bute Docks, which did 788,960 registered tons, or— | 39,448 | 255 | |
| Tyne Docks . . . | 40,000 | | |
| Grangemouth (Old Dock) . | 40,000 | 300 | |

The proportion of water area to length of quays will obviously depend on the form of the docks. The following Table, deduced from information kindly supplied by Mr. Lyster, C.E., gives examples on this head at Liverpool :—

| | Water Area. | | Lineal Quayage. | | Lineal Yards of Quay per Acre. |
|---|---|---|---|---|---|
| | Acres. | Yards. | Miles. | Yards. | Yards. |
| Liverpool Docks . . . . | 252 | 1601 | 17 | 1472 | 124·4 |
| ,, Basins . . . . | 16 | 4441 | 1 | 1088 | 168·3 |
| ,, Docks and Basins . | 269 | 1202 | 19 | 800 | 127·2 |
| Birkenhead Docks . . . . | 159 | 4535 | 9 | 110 | 99·7 |
| ,, Docks and Basins . | 164 | 2538 | 9 | 779 | 101·0 |

*Docks should be sheltered from Wind.*—After the engineer

has succeeded in designing a dock which is sufficient, in so far as the sea is concerned, it may, after all, not prove safe and convenient if it be very much exposed to the force of the wind, which, acting on the rigging and hulls of the shipping, produces a grinding action of the vessels against the quays. At Sunderland south dock, and at the docks in the Tyne, the gales of October 1863 occasioned very considerable damage, from vessels breaking adrift from their moorings and coming into collision with other vessels during high gales.

*Capacity of Basins and Docks for Trade.*—The number of vessels that can be accommodated in each acre of a basin may be termed its *available capacity*. This must obviously vary with the size of the craft which frequent the port, and with the ratio of sheltered to unsheltered acreage, or, in other words, with the exposure and the reductive power. It will therefore be highest for a dock with gates, less for an outer basin into which the waves have access, and least of all for an anchorage-breakwater or roadstead. But it also depends on the form of the basin, and on its area in relation to the class of shipping to be accommodated. It is hoped that a tolerably good approximation to the capacity of a dock will be found by the formula

$$n = \frac{1000}{t} + a$$

where $n$ represents the number of vessels per acre, and $t$ their average tonnage. $a$ is a coefficient which may perhaps be taken at from 3 to 4, according to the tonnage inversely.

| Tonnage. | Number of Vessels per Acre, by Formula $a=3$. | Number of Vessels per Acre, by Formula $a=4$. | Tonnage. | Number of Vessels per Acre, by Formula $a=3$. | Number of Vessels per Acre, by Formula $a=4$. |
|---|---|---|---|---|---|
| 100 | 13.0 | 14.0 | 350 | 5.9 | 6.9 |
| 150 | 9.6 | 10.6 | 400 | 5.5 | 6.5 |
| 200 | 8.0 | 9.0 | 450 | 5.2 | 6.2 |
| 250 | 7.0 | 8.0 | 500 | 5.0 | 6.0 |
| 300 | 6.3 | 7.3 | | | |

*Commercial Value of Docks of different Depths.*—The capacity depends not on the area only, but on the depth as well. The proportions of depths to tonnage will be referred to afterwards.

Sir J. Hawkshaw has introduced the plan of erecting a series of separate jetties on the sides of docks, instead of constructing continuous quay-walls. A large traffic can in this way be accommodated at a very considerable saving of cost. Such jetties, being formed of timber framing, render the expense of stone foundations resting on pile-work unnecessary, while they admit of the construction of continuous quay-walls of masonry, when a future expansion of the trade of the port justifies that additional expenditure. Messrs. Rendel and Robertson introduced a central tongue at the "Edinburgh" Wet Dock, at Leith, which enables a larger amount of traffic to be accommodated than would otherwise have been the case, the quay space being thus increased by about 1900 feet.

## Graving Docks, Patent Slips, Gridirons, etc.

Although graving docks are generally unremunerative, yet they largely tend to raise the character of a port; and hence almost all harbours of any importance have either graving docks, Morton's slips, or gridirons. At Liverpool, for example, there are no fewer than twenty-three graving docks, having a total length of floor of 12,489 feet.

Graving Docks are basins, fitted with gates or caissons, from which the tide-water which floats the vessel into the dock is pumped out, so as to let the carpenters get access to the ship's bottom. The sides of graving docks consist of a series of steps of masonry, called *altars,* against which timber props, generally of Gulf of Bothnia timber, are placed,

for supporting the vessel's sides as she ceases to be water-borne. Her keel is supported on blocks, generally of hard wood, but of late years they have in some places been made of cast iron. The sides, in order to save pumping, are in some places made of a curved form, so as to suit the shape of the vessel's sides. The advantages are, however, more than counterbalaced by the undue contraction of the space allotted for the carpenters, who are unable to move about easily on the sloping surface of the masonry.

Of all the different kinds of masonry which enter into the construction of marine works, there is none which requires greater accuracy of workmanship, or more careful circumspection, than the graving dock. Leakage in a wet dock, provided it does not originate at a place where it is liable to increase through time, and is of no greater extent than to depress the surface of the water a few inches, cannot be regarded as a serious evil. But in a graving dock, where the requirements are different, there should be no leakage. A very little water, accumulating on the platform of a dry dock, interferes to a serious extent with the comfort, health, and convenience of the carpenters. Although it may occasion considerable additional expense, there ought, in all cases where the soil is full of springs, to be an ample underground storage provided, by a system of drains, for receiving the leakage, which can then be pumped out periodically, as required, without ever allowing the water to rise above the platform. These underground drains are shown in cross section in Plate XVIII.

The following table gives the length, breadth of entrance, and depth of water over the sill of some of the graving docks in the United Kingdom :—

TABLE of DIMENSIONS of Different GRAVING DOCKS.

| | Length over all in feet. | Breadth of Entrance in feet. | Depth over Sill at High Water. | |
|---|---|---|---|---|
| | | | Springs in feet. | Neaps in feet. |
| Holyhead | 370 | 62 | 15 | 11.6 |
| Liverpool—Sandon, No. 1 | 565 | 60 | 21.6 | 15.9 |
| ,, ,, No. 2 | 565 | 70 | 21.6 | 15.9 |
| ,, Huskisson | 395 | 80 | 24.6 | 18.9 |
| ,, Clarence, No. 1 | 451 | 45 | 21 | 15.3 |
| ,, Herculaneum, No. 1 | 758.6 | 60 | 22 | 16.3 |
| ,, ,, No. 2 | 753 | 60 | 22 | 16.3 |
| Birkenhead—No. 1 | 750 | 50 | 25.9 | 20 |
| ,, No. 2 | 750 | 85 | 25.9 | 20 |
| ,, Morpeth | 468 | 85 | 30 | 24.3 |
| Barrow | 500 | 60 | 22.6 | ... |
| Glasson | 180 | 35 | ... | ... |
| Runcorn | 110 | 40 | 18.10 | 12.1 |
| Cardiff—West Bute | 269 | 40 | 12.6 | ... |
| ,, South Basin | 450 | 60 | 22 | ... |
| Bristol—Albion | 375 | 43 | 14.6 | ... |
| Goole | 214 | 58 | ... | ... |
| Greenock—No. 1 | 361 | 47.8 | 16 | ... |
| ,, No. 2 | 360 | 38 | 11.10 | ... |
| ,, No. 5 | 635 | 60.6 | 20 | ... |
| Port-Glasgow | 322 | 45 | 15 | 12 |
| Dumbarton | 300 | 41 | 13 | 10 |
| Clyde—Partick | 500 | 56 | 18 | 15 |
| ,, Salterscroft | 560 | 72 | 22 | 20 |
| Dundee | 500 | 53 | 20 | ... |
| Leith | 380 | 72 | ... | ... |
| Hayle | 250 | 48 | 15½ | ... |
| Plymouth, Mill Bay | 367 | 80 | 27½ | ... |
| Southampton | 475 | 80 | 26 | ... |
| Portsmouth | 346 | 66 | 20 | ... |
| | 345 | 50 | 17½ | ... |
| Aberdeen | 524 | 50 | 20 | ... |
| Belfast | 470 | 60 | 22 | ... |
| Limerick | 428 | 45 | 18 | ... |
| Londonderry | 314 | 70 | 15½ | ... |

*Iron Floating Docks.*—Mr. G. B. Rennie's docks are stated to be the first of the kind that have been made of iron. They consist of floating caissons for holding the vessel to be repaired. They are sunk by allowing them to fill with water, and are raised by pumping. The caissons are made with water-tight compartments, and they are carried up as high as the vessel's

bulwarks, excepting that through which the vessel enters and leaves. Among several advantages that have been claimed for this kind of dock may be mentioned—its independence of the rise and fall of the tide, the power of applying breast shores as in an ordinary graving dock, and the stiffness produced by the side walls. As the upper parts of the side walls or altars are always full of air, this dock may be used in deep water, and is therefore independent of the nature of the bottom.

Sir Frederick Bramwell, more than twenty years ago, designed a floating dock for St. Thomas, in the West Indies, which was capable of raising 3000 tons dead weight. The sides of this dock were not closed, but were of open girder work, and the lateral stability of the dock was obtained by means of floats worked within the girder work; the floats remained on the surface of the water, and the dock rose and fell past the floats. The sides being open, there is as much ventilation for the workmen as there is upon a slip-way.

*Mr. Edwin Clark's Hydraulic Lift*, which is situated at the Victoria Docks, London, consists of a pontoon which is filled with water and sunk between two rows of iron columns. After a vessel has been floated and steadied upon the pontoon, the whole is raised by twelve hydraulic presses of 10 inches diameter each and 25 feet lift, acting on the pontoon by means of chains. After the pontoon has been brought above the tide-level, the water is allowed to escape, when there is sufficient floating power to admit of the whole being removed to any place where the repairs can be conveniently made. The pontoons, which can accommodate vessels of a length of 350 feet, are about 320 feet long and 59½ feet broad. "The power of the hydraulic lift is 6400 tons. The largest pontoon will carry a dead load of 3200 tons in addition to its own weight."

*Patent Slips* are the contrivance of the late Mr. Thomas

Morton of Leith, and consist of a carriage or cradle working on an inclined railway, falling at the rate of about 1 in 15 to 1 in 24, and extending from about 300 feet beyond high water to several feet below the level of low water. When this carriage is let down under the water the vessel is floated above the place, and the carriage is drawn up till it catches the vessel forwards. When the ship is placed truly above the line of the carriage, powerful hauling gear, placed at the top of the slip, which is worked either by steam or hydraulic power, is set in motion, and raises the truck and ship out of the water. Messrs. Lightfoot and Thomson, who have made some improvements on slipways, state (*Min. Pro. Inst. C. E.* vol. lxxii.) that the expense of placing and hauling up a vessel weighing 2300 tons on the Penarth slipway may be taken as the wages of sixteen men for 1 hour, and three men for 2 hours. The Penarth slip is 867 feet in length, and the engine power is about 40 indicated H.P. Between the years 1879 and 1883 one hundred and thirty ships have been hauled up and repaired without the slightest accident, beyond the breakage of a few rollers at first starting. At the Wallsend slipway on the Tyne, where there are two ways placed side by side, and each a little over 1000 feet in length, 100 vessels per annum have been repaired without accident. Mr. Mitchell, shipbuilder, Newcastle-on-Tyne, says, "Speaking generally, I consider a slipway better than a dry-dock for all vessels up to 2400 tons gross register, which represents a screw-steamer about 310 feet long by 36 feet beam, and there is nothing to prevent much larger vessels being slipped; but up to this time it has not been the custom to have stronger slips than corresponds with the above size."

The following table gives the sizes of vessels which can be hauled up on some of the slipways in this country:—

| | For Tons Weight. | Depth over Cradle. | |
|---|---|---|---|
| | | Springs. | Neaps. |
| | | Feet. | Feet. |
| New Quay | 550 | | |
| Carnarvon | 400 | | |
| Liverpool | 300 | | |
| Widness | 150 | | |
| Ribble, Freckleton | 150 | 7 | |
| Preston | 260 | 8.6 | |
| Barrow | 500 | 8 | |
| Whitehaven | 330 | 8 | |
| Workington | 350 | 6.9 | |
| Maryport | 800 | 8.6 | |
| Whithorn | 550 | | |
| Ayr | 1200 | | |
| Ardrossan | 400 | 9 | |
| Greenock | 200 | | |
| Renfrew | 1000 | 15 | 10 |
| Clyde—Partick | 1000 | 15 | 12 |
| ,, Pointhouse | 1800 | 18 | |
| ,, Kelvinhaugh | 1200 | | |
| Granton | 1200 to 1300 | | |

Mr. Redman recommends that slips, which are placed in a tideway, should be laid out at a right angle to the axis of the stream.

*The Gridiron* is a simple framework of timber placed at a level sufficient to admit of vessels being floated above it during the flood-tide, and grounded upon it during the ebb, and when thus left high and dry the vessel's bottom can be examined to ascertain if it be necessary to take her into the graving dock, and trifling repairs can also be made. The gridirons at Liverpool vary from 25 feet to 36 feet 3 inches in breadth, and from 228 feet 3 inches to 509 feet in length.

*The Hydraulic and Screw Docks* used in America are chambers into which vessels are floated during the flood-tide, above a cradle which is drawn up above the high-water level, either by means of Bramah's press worked by a steam-engine, or by a powerful apparatus of screws.

*Relative Advantages of Slips and Graving Docks.*—The advantages which the patent slip possesses over the graving dock may be said to be—*First*, The cost of its construction is less. *Second*, When the fall of tide is languid, a vessel can generally be more quickly laid dry. *Third*, When so laid dry she can be more easily examined, and from the duration of the daylight being greater than in a deep graving dock, the hours in which work can be done are in this country extended during winter about forty minutes per day. *Fourth*, There is more perfect ventilation, by which the vessel's sides are sooner dried, which is of some moment with an iron ship. *Fifth*, A vessel can be hauled up long before high water, and the repairs can be at once begun; whereas with a dock the pumping occasions considerable delay. *Sixth*, While the upper part of the slip is occupied, an additional vessel may be taken up for a shorter time than its predecessor, without interrupting the workmen.

The advantages afforded by a graving dock, on the other hand are—*First*, That, although its construction is more costly, it is nevertheless, if properly built, unquestionably a more durable structure—the rails, rollers, carriages, and chains, connected with the slip, being liable to derangement, which entails occasional repair. *Second*, The management of the graving dock is simple, and involves comparatively little superintendence; whereas that of a slip is intricate, and requires more than mere nautical skill. *Third*, The working of a graving dock is equally simple for large or small vessels, while it is undeniable that the raising of a large vessel on a slip is a delicate operation, and should be attempted only under the direction of persons thoroughly versed in such matters, and having ample mechanical resources at command. *Fourth*, The graving dock possesses the advantage, which is sometimes

important, of affording the means of more easily filling a vessel with water, so as to detect leaks which may not be discoverable by other means. For this purpose a nozzle to receive a flexible tube should be fixed into the dock-gates. *Fifth*, Where double gates are provided, the water contained in the dock affords a certain limited power of scouring the forebay and entrance, an advantage which is of course not possessed by a slip. *Sixth*, In any rapid land current, or strong tideway, it is a much easier process to dock a vessel than to land her safely on the cradle of a slip—an operation which, when incautiously gone about, has been in some cases attended with serious consequences even in sheltered situations. *Seventh*, The graving dock need not interfere with the set of the currents, whereas a slip which projects a long way seaward of low water may deflect them and produce shoals in the channel. *Eighth*, Mr. Mallet has remarked that the strains on a ship's timbers are more direct than when she is on a slip, especially when she is leaving the cradle. The late Mr. J. M. Balfour suggested, in order to meet this objection, that the cradle for a slip might be made of a wedge shape, so that its upper surface shall be parallel with the horizon, or that the back end should even be tilted slightly, so as to give a *bite* on the vessel and prevent her from slipping.

The relative advantages of the other contrivances for the repair of ships already described may be judged of by comparing them with each other, in a similar manner to that which has been done with the graving dock and slip.

*Shipbuilding Stances.*—A frontage of from 70 to 90 feet is about the average width which may be allowed for each shipbuilding stance.

*Dock-Gates.*—Mr. P. W. Barlow has given the following formulæ for the strength of dock-gates :—

*Formula for Straight Gates.*

$\phi$ = horizontal angle or ("sally") between pointing sill and line joining heel-posts of the two leaves.

W = pressure on the length of the gate with any head and for a given depth of the gate.

S = whole transverse strain at angle $\phi$.

$$S = \tfrac{1}{2} \text{ W sec. } \phi + \frac{1}{20} \text{ cosin } \phi.$$

From this Mr. Barlow has deduced that the salient angle, where the strain is the minimum, is 24° 54′, but as the length of the gate increases with the secant, the strength will not at this angle be the greatest with a given section of timber.

The *sally* or angle which gives the greatest strength, with a given section of timber, is stated by him as 19° 25′.

*Formula for Curved Gates.*

When $\theta$ is the salient angle, or camber of the beam, formed by a chord line drawn from the heel to the mitre-post, with the tangent to the curve of the gate—

$$S = \tfrac{1}{2}\text{W}\left\{ 1 - \frac{\sin.\ \theta}{\sin.\ (2\ \phi - \theta)} \right\}.$$

There is great difference of opinion among engineers as to the strain to which dock gates are subjected, and the reader is referred for further information to the 18th and 31st volumes of the *Minutes of Proceedings of the Institution of Civil Engineers.* In these discussions Mr. Brown pointed out an error in Mr. P. W. Barlow's paper, which stated that the line of pressure at the mitre-posts would always be a tangent to the curve of the separate gates, whereas that line must always be at right angles to the centre line of the lock, and could only be a tangent to the curve when the two gates

formed a segment of a circle, or, as Sir F. Bramwell says, at all events, that their junction at the mitre-posts formed, at that point, part of a continuous curve. Mr. Brown gives elaborate formulæ suited to meet a yielding or deflection of the structure, which he alleges must always take place. Sir F. Bramwell states, and we think justly, that when the gates form when closed a segment of a circle they cannot be subjected to transverse strain, and that the whole of the gates would be subjected simply to compression. Mr. R. P. Brereton very properly suggests that when the gates are of malleable iron the boiler-plate should never be less than $\frac{1}{4}$ of an inch thick, whatever the formula may indicate.

Where $l$ represents the length of one half of a straight or cambered malleable iron gate, $w$ the distributed pressure over the length of the leaf taken on a given element of the gate, bounded by two horizontal planes one foot apart, $t$ the thickness of framework of gate or distance between the two skins, $s$ the transverse strain in middle of gate, $\theta$ half of the mitreing angle—*i.e.* the angle formed by meeting of gates—all the dimensions being in feet, and weight in tons—

$$s = \frac{\frac{1}{2}wl}{4t}$$

$\frac{s}{4}$ = sectional area of metal on compressed side in inches.

$\frac{s}{5}$ do. do. on extended side do.

$\frac{1}{2}\, w \tan\theta$ = compressive strain produced by other leaf of gate.

Mr. Kingsbury adds half of this compressive strain to the strain representing the compression due to the transverse pressure, and deducts it from the same amount for the extension; and these results being divided as before by 4 and 5 respectively, being the allowances per square inch of metal

for compression and extension, give the areas for each. He, however, expresses a doubt whether the whole of the compressive strain from the other gate may not perhaps come upon the compressed section. The sections close to the posts he takes as requiring to resist the compression due to transmitted pressure only, or $= \frac{\frac{1}{2} w \tan \theta}{4}$.

*For Cylindrical Gates.*—Mr. Kingsbury gives:—When $p =$ the pressure per unit of surface, and $r$ the radius of curvature—

$$\frac{pr}{4} = \text{sectional area of metal in square inches.}$$

*Gates placed in exposed situations.*—It must be remembered, in designing gates which are exposed to the waves, that they should be made stronger than the formulæ require. At Seaham the gates are 35 feet in width; and on the supposition of the maximum waves outside being 13½ feet in height, as at the port of Sunderland, which is only a few miles farther north, the formula for reduction (p. 165) indicates 4 feet as the height at the sea gates. But the dock is not available at such times, for whenever the waves exceed about 2 feet, it is found that the gates cannot be properly worked. At the North Dock of Sunderland the gates, which are 51 feet wide, cannot be worked when the waves are 3 feet high; while the greatest height of waves at the South Dock gates, which are 60 feet wide, is 8 feet, and they cannot be worked when the waves are 2 feet 6 inches high.

It might at first sight appear that the difficulty of working dock gates, when exposed to the action of waves, should increase as the squares of the breadths of the gates; but owing to the manner in which the resistances are distributed, this

does not seem to be the case. Where $h$ = height of waves and W = breadth across gates, both in feet, we may take $h = \frac{60}{W}$, and when $h$ has not been ascertained, and $d$ is length of fetch in miles, $W = \frac{60}{1.5\sqrt{d} + (2.5 - \sqrt[4]{d})}$.

*Caissons* are frequently employed instead of gates, especially for graving docks, and are the invention of the late General Bentham. Caissons, which are of three kinds—floating, sliding, and rolling—are generally constructed of malleable iron plates, and are sometimes made in the form of a ship's hull, and sometimes have vertical sides. They fit into checks made for their reception in the side walls of the entrance to the dock. They require to be very carefully ballasted, and to be most accurately fitted to the masonry on the sides and bottom, and even when they are faced with timber which has been finely dressed and fitted, coal cinders are often needed to make the joints watertight. At high water they are floated into the grooves, and are then scuttled, by admitting the water into the interior chamber. When a vessel has to leave the dock the water is again pumped out, and the caisson is then floated out of its place and taken into the river or harbour, so as to be out of the way of the vessel which is leaving. General Bentham says caissons are cheaper than gates, occupy less room, are more easily repaired, and the same caisson may be used for different places at different times, while they answer for roadways, and require less labour for opening.

The caisson at Keyham was designed by Mr. Scamp, Deputy-Director of the Admiralty Works, and is 80 feet wide and 43 feet deep, with an air-chamber at the bottom. When raised a few inches above the bottom, the caisson is drawn

back into a recess or chamber in the side walls. The total weight is 290 tons, and the deflexion was $\frac{7}{8}$ inch near the bottom when the pressure over the whole surface was 2000 tons. The time occupied in opening and closing the entrance at Keyham is ten minutes and eight minutes respectively. The cost was about £10,000.

The wrought-iron caisson and folding bridge at the Garvel Graving Dock, Greenock, was designed by Mr. Kinipple, and has been patented by him. He has given the following description :—"The bridge is of sufficient strength to admit of a locomotive passing over it. Instead of being floated out of its berth at great loss of time and labour, as has hitherto been usual with ordinary caissons upon vessels entering or leaving a dock, the caisson is carried upon trollics running upon plate rails, or upon rollers fixed on the floor of the caisson chamber; and, by means of a small hydraulic apparatus, is drawn into or out of a chamber or recess under the quay, as may be required. All the invert and stop quoin faces of the entrance, against which the caisson with its teak meeting faces slides and abuts, are of polished granite. The bridge, by coming in contact with curved plates, lowers or raises itself during the process of opening or closing. Among the many advantages to be obtained in connection with this invention, it may be mentioned that the caisson may be opened or closed in a few minutes, at any time of tide, and in almost any sea or weather, or during a considerable current through the entrance. It also avoids the cost of heavy swing bridges with expensive foundations, opening and closing machinery, etc. The caisson may be also floated in the ordinary way, and removed to any graving dock for repairs, or be placed outside the entrance, to act as a coffer-dam in the event of its being necessary to get at the sill of the dock or other parts of the

entrance works below low water." This caisson, which is 66 feet in length, with lowering bridge and hauling machinery, cost £7797. It can be opened or closed at any stage of the tide, by the engineman, at a cost of about 3d.

The caisson designed by Mr. John M'Connochie, shown on Plate XVII., is that of the graving dock at Cardiff. It is 60 feet long, 26 feet in greatest width and 13 feet in least width at the centre, and 30 feet 6 inches in depth, and is constructed of angle iron frames, columns, and beams, and skin plates, with oak stems and keel, and fir deck planking. It is divided by a water-tight deck and by bulkheads into sixteen compartments, communicating with each other by small side slide-valves for water-ballast arrangements.

The gates for graving or dry docks sustain a greater pressure with the same rise of tide than those of wet docks, and should therefore be made correspondingly stronger.

Examples of gate-construction, as carried out at different works, will be found in Plates XIV. XV. and XVI.

*Dock Walls.*—Mr. Giles recommends that dock walls should always be made of sufficient strength to resist a pressure of water equal to their height. Minard assigns four-tenths of the height for the thickness, and Rankine takes the ordinary thickness at from one-third to one-half of the height. Some examples will be found in Plate XIX.

# CHAPTER X.

## MATERIALS, KINDS OF MASONRY, IMPLEMENTS, ETC.

**Early Use of Timber—Marine Insects—Experiments at Bell Rock—Greenheart not an entire protection against Insects—Protection of Timber—Creosoting—Pile-work—Screw-Piles—Screw-Moorings—Advantages of Timber over Stone—Destruction of Stone—Durability of Wrought-iron, Cast-iron, and Bronze—Dressing and Mode of assembling Masonry—Settling of Rubble—Edge Work—Rhomboidal Stones—Size of Materials—Treenailing—Portland Cement, Rubble, and Concrete—Lifting and Setting Concrete Blocks—Voids between Blocks of Concrete—Passing Concrete through Water—Monolithic Structure of Cement, Concrete, or Rubble—Concrete Cylinder Foundations—Concrete Blocks at Dublin—Iron Concrete—Asphaltic Masonry and Cement—Carbonite Cement—Measurement of Proportions of Materials for Cement—Pontoons—Depositing Pierres Perdues—Greenheart Staging—Iron Lattice-work.**

*Early Use of Timber.*—The employment of timber in harbour works is of great antiquity. It seems first to have been used in forming boxes which were filled with stones, and at a more recent period in the formation of open frameworks through which the current could pass freely. Vitruvius mentions moles, consisting of timber filled with stones and cement, as having been used by the harbour-builders in his days. These structures, he says, "which are built in the water, are thus executed. The sand of the country, which extends from Cumæ to the promontory of Minerva, is procured and mixed with lime in the proportion of two to one; then in the intended place, fences of oaken piles, bound with chains, are fixed in the water, and firmly united. When this is done,

the ground at the bottom of the water between these fences is by means of transtilli (!) cleaned and levelled, and rubble stones, with mortar mixed in the manner before written, is thrown in, till the space between the fences is quite full."[1] It was probably to some such work that Horace refers in Ode 1st, lib. iii.—

> "Contracta pisces aequora sentiunt,
> Jactis in altum molibus ; huc frequens,
> Caementa dimittit redemptor."

A harbour contract, in all probability the earliest which has been preserved, appears in the *Registrum Nigrum de Aberbrothoc*—a collection of ancient documents printed by the Bannatyne Club, and edited by the late Mr. Cosmo Innes, Professor of Antiquities in the University of Edinburgh. The contract, which is between the Abbots and Burgesses of Aberbrothoc (Arbroath), bears date 1394, and provides in the following terms for the erection of a haven by the Abbots, while the Burgesses undertake to find the materials and to clear the ground :—

"Tandem . . . in hunc modum restat concordatum videlicet quod Abbas et conuentus supradicti loco peritorum indicio eminenciori portum salutarem dicto burgo sumptibus suis . . . ad quem et in quo naues applicare valeant et in ipso applicantes ipsius maris fluxibus et refluxibus non obstantibus salue quiescere et stationem habere securam omni celeritate possibili edificabunt constructum edificatumque imperpetuum sustentabunt burgenses vero burgi supradicti in huiusmodi portus edificacione auxilium tale exhibebunt quod sumptibus suis lapides omnes sabolum et alia portus constructionem impediencia removebunt ac semel

[1] The *Architecture* of M. Vitruvius Pollio ; translated by W. Newton, architect. London, 1791. Vol. i. p. 121.

dictum portum purgabunt a sabolo et lapidibus cum pro dicto opere conueniens fuerit et necesse continuantes eciam dictam mundacionem a dicti portus fabrice inicio usque dictum opus fuerit perimpletum . archas omnes pro portu ordinatas ad consilium magistrorum implebunt et locabunt ac lapidibus onerabunt ad primam edificacionem portus supradicti instrumenta certa ad hec scilicet vangas, tribulos, et gavyllox ferreos eorum expensis inuenient alia · vero instrumenta et onera Abbas et conuentus." Such is the account of the practice of Scotch engineers 491 years ago, from which it appears that the structures then erected consisted of timber chests filled with rubble stones.[1]

The earliest drawing of timber piers that I have met with is that of the ancient Port of Dunkirk, in 1699, a copy of which, from Belidor's *Architecture Hydraulique*, is given in Plate IX. This kind of structure is still not uncommon on the coasts of the English Channel.

*Destruction of Timber by Marine Insects.*—In sheltered bays, where a deep-water landing-place is all that is required, and where the bottom is sandy or soft, timber may be employed with great advantage. Even in somewhat exposed situations it can also be used for tidal harbours; but the fatal evil in places where there is no admixture of fresh water is its rapid destruction by marine insects. In the Atlantic Ocean, the *Teredo navalis* is very destructive to timber, and is not, as some writers suppose, of recent appearance on our shores. Upwards of 300 years ago the ravages of these

[1] Professor Innes appends a point of interrogation to the word "*tribulos.*" On examining Agricola *De re metallica*, printed at Basil in 1561, and which contains descriptions of different implements, I found the *tribuli* described as a kind of *hammer* for breaking up ore. The tribuli were then obviously intended for breaking the stones with which the *archæ* or timber chests were to be filled.

animals attracted much attention in Scotland, and gave rise to the most absurd theories as to their generation; and although the resemblance, one would think, is sufficiently obscure, they were then firmly believed to be young sea-fowl of the kind called *Klaiks*.[1] The barnacle (*Lepas anatifera*) was formerly supposed to be the young of the barnacle goose, as the modern scientific name indicates. The form of the barnacle shell has perhaps a faint resemblance to a pair of bird's wings, and there is a feathery plume, which the animal can thrust out, and which of course helps the resemblance. At many places in the German Ocean, the *Limnoria terebrans*, which was first discovered by the late Mr. Robert Stevenson at the Bell Rock Lighthouse in 1810, destroys most kinds of timber. Mr. Stevenson found[2] that Memel timber was destroyed by the Limnoria at the Bell Rock, at the rate of about *one inch inwards per annum.* At Kingstown, the *Chelura terebrans* has also proved very troublesome; and Mr. Rawlinson has found the common mussel nearly as destructive to timber as the Teredo. The Limnoria and the Teredo are found to eat most rapidly between the bottom and low-water mark, but above low-water the damage is not so great; and, what is singular, they do not appear to exist at all below the bottom, where the pile is covered with sand. This result does not, however, agree with Mr. Hartley's experience at Liverpool, where the parts which were alternately wet and dry were noticed to decay faster than those which were constantly immersed.

*Experiments at the Bell Rock.*—Mr. R. Stevenson devoted much attention to the ravages of the *Limnoria terebrans* at

[1] Hector Boece's *Kroniklis of Scotland*, published at Edinburgh about 1536.

[2] *Account of the Bell Rock Lighthouse*, by R. Stevenson, F.R.S.E. Edinburgh, 1824.

the Bell Rock, where he established a regular series of observations, beginning in 1814, which were made by fixing pieces of different kinds of timber to the rock, and getting regular reports on their decay. He found that *greenheart, beef-wood, African oak*, and *bullet-tree*, were scarcely attacked by worms, while *teak* stood remarkably well, and *locust* tolerably well although suffering at last.[1] He subsequently made other experiments, the results of which are also appended in the following Table :—

[1] Dr. Bancroft describes *Greenheart* or the Sipieri tree to be "in size like the locust tree, say 60 or 70 feet high : there are two species, the black and the yellow, differing only in the colour of their bark and wood. The greenheart of Jamaica and Guiana is the *Laurus chloroxylon* of botanists ; it is also called cogwood in the former, and Sipieri in the latter locality." . . .

"Botany Bay Oak, sometimes called *Beef-wood*, is from New South Wales ; it is shipped in round logs from 9 to 14 inches diameter. . . . *Casuarina stricta* is called she oak, and also beef-wood." . . .

"The *African oak*, or *teak*, as it is called, is not a species of *Quercus*. . . . *Teakwood* is the produce of the *Tectona grandia*, a native of the mountainous parts of the Malabar coast, and of the Rajahmundry Circass, as well as of Java, Ceylon, and the Moulmein and Terrasserim coasts. . . . In twenty-five years the teak attains the size of 2 feet diameter, but it requires 100 years to arrive at maturity. . . . African teak does not belong to the same genus as the Indian teak ; by some it is thought to be a *Euphorbiaceous* plant, and by Mr. Don to be a *Vitex*." . . .

"*Bullet-wood* from the Virgin Isles, West Indies, is the produce of a large tree with a white sap ; the wood is greenish hazel, close and hard. It is used in the country for building purposes, and resembles the greenheart. . . . Another species so called is supposed to come from Berbice."

"*Locust-tree.*—The locust-tree of North America is *Robinia pseudacacia.* The wood is greenish yellow, with a slight tinge of red in the pores ; it is used like oak. Locust is much esteemed for treenails for ships. . . . The locust-tree of the West Indies and Guiana is *Hymenea Courbasil* (Somiri), a tree from 60 to 80 feet in height, and 5 or 6 feet in diameter. The colour of the wood of the West India locust-tree is light reddish-brown, with darker veins, and the mean size 36 inches."—*Descriptive Catalogue of the Woods commonly used in this country, with Botanical Notes*, by Dr. Royle. London, 1843.

TABLE showing the different kinds of Timber which were exposed to the attacks of the *Limnoria terebrans* at the Bell Rock in 1814, 1821, 1837, 1843, with their durabilities.

| Kind of Timber. | Decay first observed. | Unsound and quite decayed. | Quite sound for | Remarks. |
|---|---|---|---|---|
| | yrs. mo. | yrs. mo. | yrs. mo. | |
| [1]Greenheart .. .. .. | .. | .. | 19 0 | [1] Affected in one corner. |
| Teakwood .. .. .. | .. | .. | 13 0 | |
| Beef-wood .. .. .. | .. | .. | 13 0 | |
| Treenail of Bullet-wood .. | .. | .. | 5 0 | [2] A little holed at one end under- |
| [2]Beech, Payne's patent pro. | 10 7 | .. | .. | neath. |
| [3]Teakwood .. .. .. | 5 6 | .. | .. | [3] Nearly sound 7½ years after being |
| [4]African Oak .. .. .. | 5 6 | .. | .. | laid down. |
| Do. do. .. .. | 4 11 | 10 0 | .. | [4] Nearly sound 7½ years after being |
| English Oak, kyanised .. | 4 7 | 10 0 | .. | laid down. |
| Teakwood .. .. .. | 4 7 | 12 0 | .. | |
| [5]American Oak, kyanised .. | 4 3 | .. | .. | [5] Decaying but slowly 5 years and |
| British Ash .. .. .. | 3 0 | 5 0 | .. | 7 months after being laid down. |
| Scotch Elm .. .. .. | 3 0 | 5 0 | .. | |
| Ash .. .. .. .. | 2 11 | 4 3 | .. | |
| English Elm .. .. .. | 2 11 | 4 7 | .. | |
| [6]Plane Tree .. .. .. | 2 11 | .. | .. | [6] Decaying but slowly 5 years and |
| American Oak .. .. | 2 11 | 4 7 | .. | 7 months after being laid down. |
| [7]Baltic Red Pine .. .. | 2 9 | 4 3 | .. | [7] A good deal decayed when first |
| English Oak .. .. .. | 2 4 | 4 7 | .. | observed. |
| [8]Scotch Oak .. .. .. | 2 4 | .. | .. | [8] Much decayed when first ob- |
| Baltic Oak .. .. .. | 2 4 | 4 8 | .. | served. |
| Norway Fir .. .. .. | 2 4 | 3 1 | .. | |
| Baltic Red Pine, kyanised .. | 2 4 | 4 7 | .. | |
| Pitch Pine .. .. .. | 2 4 | 4 8 | .. | |
| American Yellow Pine .. | 2 4 | 3 7 | .. | |
| American Red Pine .. .. | 2 4 | 3 1 | .. | |
| Do. do., kyanised.. | 2 4 | 4 7 | .. | |
| Larch .. .. .. .. | 2 4 | 4 8 | .. | |
| [9]Honduras Mahogany .. | 2 1 | .. | .. | [9] Nearly sound 3½ years after being |
| Beech .. .. .. .. | 1 9 | 3 1 | .. | laid down. Washed away 6 |
| American Elm .. .. | 1 9 | 3 1 | .. | months later. |
| Treenail of locust .. .. | .. | 5 0 | 3 0 | |
| British Oak .. .. .. | 1 6 | 5 0 | .. | |
| American Oak .. .. | 1 6 | 5 0 | .. | |
| Plane Tree .. .. .. | 1 6 | 5 0 | .. | |
| Honduras Teak treenails .. | 1 6 | 5 0 | .. | |
| Beech .. .. .. .. | 1 6 | 5 0 | .. | |
| Scotch Fir, teak treenails .. | 1 6 | 3 0 | .. | |
| Do. from Lanarkshire .. | 1 6 | 3 0 | .. | |
| Do. do. .. | 1 6 | 3 0 | .. | |
| Do. locust treenails .. | 1 6 | 3 0 | .. | |
| Memel Fir .. .. .. | 1 6 | 5 0 | .. | |
| [10]Pitch Pine .. .. .. | 1 6 | 2 6 | .. | [10] Going fast when first observed. |
| English Oak .. .. .. | 1 1 | 3 1 | .. | |
| Italian Oak .. .. .. | 1 1 | 3 6 | .. | |
| Dantzic Oak .. .. .. | 1 1 | 2 6 | .. | |
| English Elm .. .. .. | 1 1 | 1 6 | .. | |
| Canada Rock Elm .. .. | 1 1 | 1 6 | .. | |
| Cedar of Lebanon .. .. | 1 1 | 2 6 | .. | |
| Riga Fir .. .. .. | 1 1 | 1 6 | .. | |
| Dantzic Fir .. .. .. | 1 1 | 1 6 | .. | |
| Virginia Pine .. .. .. | 1 1 | 1 6 | .. | |
| [11]Yellow Pine.. .. .. | 1 1 | 1 6 | .. | [11] A good deal gone 18 months after |
| Red Pine .. .. .. | 1 1 | 1 6 | .. | being laid down Swept away |
| [12]Cawdie Pine.. .. .. | 1 1 | 1 6 | .. | by the sea 7 months afterwards. |
| [13]Polish Larch .. .. | 1 1 | 1 6 | .. | [12] A good deal decayed when first |
| Birch, Payne's patent pro. .. | 0 10 | 1 10 | .. | observed. |
| American locust treenails .. | 0 8 | 3 0 | .. | [13] Going fast when first observed. |

Greenheart timber, though not absolutely impenetrable, as appears from Mr. Stevenson's experiments, is the great specific in seas where the worms are destructive. Greenheart appears to have been first used as a material by Mr. J. Hartley, who, in 1840, published, in the Minutes of Institution of Civil Engineers, an account of its virtues, as ascertained at the Liverpool Docks. Its cost is, however, considerably greater than Memel, or than most of the other timbers in common use. Mr. D. Stevenson gives the following account of recent experience:—"It was, I believe, for the first time employed for staging at Wick Bay, where logs of pine could not withstand the waves; and it was on removing the temporary greenheart staging, that had been in use from two to four years at Wick, that I first became fully aware that the Limnoria would perforate that timber. Some of these logs were found to have been attacked by the Limnoria throughout the whole surface, extending from about low-water mark to the bottom. This discovery caused no little surprise and regret, as engineers had always looked on greenheart as proof against destruction by marine insects; but being the first, and it was hoped perhaps an isolated instance, I did not consider it necessary at once to record the fact.

"I have since, however, received a specimen of timber taken from one of the piles in the steamboat pier at Salen, in the Sound of Mull, which was erected four years ago, the main piles being made of sound greenheart, and I find that in this locality also the Limnoria has commenced to perforate the timber.

"In both of these instances sufficient time has not elapsed to allow the wasting to make great progress, but in both cases the perforators have penetrated into what is unquestionably sound fresh timber; and therefore this result conflicts with

certain other experiments, such as those made at the Bell Rock, where the greenheart remained nearly sound after nineteen years' exposure.

"The joint paper of Dr. Maclagan and Dr. Gamgee on greenheart in the Society's 'Transactions' states that by subjecting greenheart *wood* to a process identical with that used for the extraction of sulphate of bebeerine from the *bark*, a product is obtained possessed of an intensely bitter taste, and not differing perceptibly from the sulphate of bebeerine. This may account for wounds produced by a splinter of greenheart not readily healing.

"I am also disposed to think that it is to the existence of this alkaloid in the timber, and not to its hardness, that its undoubted power of withstanding, in certain cases and for a certain time, the action of the Limnoria is due; and it would be interesting to discover whether the wasted portions of greenheart at Wick and Salen produced bebeerine in a smaller degree as compared with sound timber. It is possible, as suggested by Sir Robert Christison, that long-protracted immersion in sea-water may so counteract the preservative principle, due to the bebeerine in the timber, as to render it open to attack. It is also possible that the greenheart now imported in such large quantities has degenerated, like the 'Crown Memel,' which, it is well known, cannot be procured of the same high quality as formerly. Change of soil, moreover, affects the growth of trees, and is perhaps sufficient to account for the great variations in the quality of foreign-grown timber.

"In any view of the case, however, it seems necessary, in connection with my former notice, to make known the fact that greenheart, *as now imported*, and generally used in marine works, is not, as was hitherto supposed to be the case, wholly

proof against the ravages of the *Limnoria terebrans*, suggesting, perhaps, increased care in its selection, although I believe it must still be regarded as the most durable timber that can be employed in such works. It is almost unnecessary to add that these observations refer to localities where the timber is exposed to what may be termed *sea-water*, and not to situations where, from admixture of fresh water or other causes, the ravages of the Limnoria are greatly mitigated, or altogether unknown."[1]

*Protection of Timber.*—Memel logs for the interior piles of piers, where they will not be liable to suffer by abrasion from ships, might perhaps be clad with greenheart planking at those parts which are exposed to the worm. *Copper sheathing and scupper nailing* are often successfully employed as protections for piles in exposed situations. The scupper or broad-headed nails are driven so closely as almost to touch each other; and the oxide of iron enters into the outer skin of the wood, which becomes hard enough to resist the worm. *Green twigs of pine or other wood*, when placed among piling, have been found, in Sweden, to prevent the attacks of the worm. *Breaming* or scorching timber, and saturating it, while hot, with a mixture of whale oil and thin coal tar, also forms a temporary protection. The *creosoting process*, patented by Mr. Bethel, and which has been so largely and so successfully introduced for preventing the decay of railway sleepers, bridges, etc., has recently been much employed in the construction of timber works subject to the attacks of marine insects. Mr. Bethel recommends that the timber for such purposes should receive 10 lbs. of creosoting fluid to each cubic foot, which is tested by weighing each log before and after it leaves the creosoting tank. It was confidently be-

[1] *Proceedings Roy. Soc. Edin.*, vol. viii. p. 781.

lieved that Mr. Bethel's very important invention, which had proved so efficacious in preventing the ordinary decay of wood on land, would be found equally useful for timber immersed in sea-water. It was first found, as might indeed have been readily anticipated, that it would not answer the end expected, if the timber were cross cut, or scarfed, *after* the fluid had been injected. But it was afterwards discovered that the woody fibre was eaten, even although the outer skin had suffered no injury of any kind after being in the tank. Mr. D. Stevenson has lately directed attention to this fact, and has proved that at Scrabster, Invergordon, and other places where the timber was thoroughly creosoted, it has been very much destroyed by the worm, which undoubtedly eats the timber freely, even though it be still black with the creosote, and continue to emit its pungent odour. Mr. A. M. Rendel, in his evidence on Leith Harbour, asserts, from the experience he has had at that port, that the life of timber fully creosoted is limited, at Leith Harbour, to about 20 years.[1]

*Pile-work.*—Dr. Rankine's formulæ[2] for the strength of pile-work are, when—

P is greatest load which a pile is to bear without sinking farther, in tons;
W, the weight of ram used for driving it, in tons;
$h$, the height from which the ram falls, in feet;
$l$, the length of the pile, in feet;
$x$, the depth it is driven by the last blow, in fractions of a foot;
S, its sectional area, in square inches;
E, its modulus of elasticity;
(Approximate values of E in tons on the square inch—elm, 400 to 600; beech, about 600; greenheart, 500 to 600)—

[1] Evidence, Select Committee on Leith Harbour. 1860.
[2] *Useful Rules and Tables.* By W. J. M. Rankine. Lond. 1866, p. 183.

$$x = \frac{Wh}{P} - \frac{Pl}{4ES}.$$

The pile must be driven until the additional depth gained by each blow of the energy $Wh$ becomes not greater than $x$.

The energy required for the final blow is—

$$Wh = \frac{P^2 l}{4ES} + Px.$$

And, finally—

$$P = \sqrt{\left(\frac{4ESWh}{l} + \frac{4E^2S^2x^2}{l^2}\right)} - \frac{2ESx}{l}.$$

Professor Stevelly gives a simpler formula, which assigns a considerably smaller value to the safe load.

When W is weight of ram, in tons;
W′, weight of pile, in tons and decimals;
$h$, height of fall, in feet and decimals;
$d$, depth yielded, in feet and decimals;
L, safe limit of load, in tons;

$$L = W\left(\frac{W}{W + W'}\right)\left(\frac{h}{d}\right).$$

*Mr. Mitchell's Screw-Piles.*—The ingenious invention of Mr Mitchell of Belfast, by which piles can be screwed into the ground, has been applied by him to harbour purposes. In quicksands it has often been found impossible to drive piles satisfactorily, and after they have been driven they have been known to start up again. Whereas piles fitted with screws on their ends are not only easily put down, but take a remarkably firm hold of the ground. Screws have been used as large as 4 feet in diameter, and have been made to penetrate clay and sand to the depth of 26 feet. The pier at Courtown, in the county of Wexford, is constructed on this principle, which has also been successfully employed for lighthouses and beacons.

*Screw-Piles.*—The load supported by a screw-pile in practice ranges, according to Rankine, from 3 times to 7 times the weight of the earth which lies directly above the screw-blade.

*Screw-Moorings.*—One of the most valuable of the applications of the screw is that for the mooring of vessels in roadsteads, rivers, and harbours. Screw moorings vary in depth from 8 to about 18 feet, depending on the tenacity of the material and on the strain to which they are to be subjected.

*Advantages of Timber over Stone as a Material.*—It is much to be regretted that greenheart, which so long resists the worm, is still expensive in this country, and that some simple and economic specific against the worm has not been discovered for protecting Memel and the cheaper kinds of pine. The grand desideratum in harbour works, which is the *want of continuity in the structure,* would be supplied by timber work. It follows from the known laws of fluids that each individual stone in a pier which is equally exposed throughout its whole length, is subjected to a force which it can only resist by its own inertia, and the friction due to its contact with the adjoining stones. The stability of a whole work, if not cemented by hydraulic mortar, may therefore be perilled by the use of small stones in one part of the fabric, while it may be in no way increased by the introduction of heavier stones into other parts. By the use of long logs of timber, carefully bolted together, a new element of strength is obviously obtained.

*Destruction of Stone.*—Even solid rock is destroyed by the persevering efforts of the Pholades and Saxicavæ. The Pholas perforates wood, limestone, hard and soft argillaceous shales, clay, and sandstone. Though the Saxicavæ, which attack the limestone blocks of the Plymouth breakwater, do not penetrate more than half a foot from the surface, yet their holes are so close to each other as to make it easy to break off the outer

portions of the stone, when a new surface is laid open to their attack.[1]

*Destruction of soft Rock* in situ *by the Pholas.*—I observed at Kirkcaldy a curious example of very serious mischief which had been caused by the gradual excavations of the Pholas. The quay-walls and gate-chamber of the scouring-basin, which is also used as a wet dock, were built on beds of shale or till, which I am told formed originally a most secure and incompressible foundation. But several years after the work was finished the masonry gradually settled, and is now so much sunk that both the quays and gate-chamber have become ruinous. Persons on the spot believed that the settlement was occasioned either by want of strength in the masonry, or by the sinking of old coal workings which were supposed to exist below the harbour. But on examining the bottom, I found it completely honeycombed by the Pholas, which, getting access through the water in the dock, had perforated the shale-beds on which the walls rested, and which, before the dock was excavated, had never been exposed to their attacks. So firm and compact had the shale been at first that the masonry, instead of being carried down to the level of the bottom of the dock, was founded on the top of the shale.

As the number of perforations in the shale increased, its power of resisting compression must obviously have gradually decreased in a corresponding degree, till at length the weight of the quay-wall would begin to crush the shale. But it is evident that the settlement thus occasioned could not have been equal over the whole area of the foundation, because the outer portions of the shale, being next the water, would

[1] *History of British Mollusca.* By Edward Forbes and S. Hanley. Lond. 1853. Vol. i. p. 104.

necessarily be more honeycombed than the interior, and hence the outer facing of the walls would sink more than the *backing*, which was precisely what was found to take place.

## IRON.

*Mr. R. Stevenson's Experiments on the Durability of Iron.* —In addition to the experiments on timber, twenty-five different kinds and combinations of iron were tried at the Bell Rock, including specimens of galvanised iron. All the ungalvanised specimens were found to oxidise with much the same readiness. The galvanised specimens resisted oxidation for three or four years, after which the chemical action went on as quickly as in the others. Although the association of zinc with iron protects, so long as it lasts, the metal with which it is in contact, it must be remembered that this immunity is obtained at the expense of the zinc, the tendency of which to oxidisation is proportionally exalted so soon as any part of the iron is exposed.

*Mr. George Rennie's Experiments on the Durability of Wrought-iron, Cast-iron, and Bronze.*—Mr. George Rennie made experiments in 1836 on one-inch cubes of wrought-iron, of cast-iron, and of bronze, with reference to the question of their eligibility for lighthouse purposes. In narrating his experiments and their results Mr. Rennie says—

"The cubes, being previously weighed, were then plunged into a saline dilution considerably stronger than sea-water, as follows:—

| | | |
|---|---|---|
| Muriate of Soda, . | 122 | grains. |
| Muriate of Magnesia, | 25 | „ |
| Muriate of Lime, . | 6 | „ |
| Sulphate of Soda . | 30 | „ |
| | 183 | grains dissolved in $10\frac{1}{2}$ oz. of Thames water. |

"The cubes were then taken out of the water, after being immersed seventy hours in separate vessels. The cast-iron was found to have lost $\frac{1}{3307}$th part of its weight, while the wrought-iron had only lost $\frac{1}{6610}$th of its weight, being in the proportion of *two lost by the cast-iron to one only lost by the wrought-iron;* while the brass cube only lost $\frac{1}{10000}$th part of its weight, which is decisively *in favour of bronze, in the ratio of three to one.*

"The cast and wrought iron cubes, being accurately weighed, were again plunged into a strong dilution of 1 measure of muriatic acid to 25 measures of Thames water, when, after remaining twenty-one hours, the cast-iron cube was found to have lost $\frac{1}{33}$d of its weight, and the wrought-iron only $\frac{1}{258}$th of its weight, being in the proportion of 8 *to* 1 *in favour of wrought-iron.*"

*Ancient Bronze Relics.*—The wonderful durability of bronze is well shown by the axe-heads and other articles belonging to prehistoric periods, which are from time to time discovered in making excavations in gravel-drift. Five bronze axes were turned up in the works of excavation for the Edinburgh and Leith sewerage. Nothing could exceed the sharpness of the edges and the projections of the ornamentation, and they were all remarkably free from oxide.

*Mr. Mallett's Experiments.*—The important experiments of Mr. Mallett on specimens sunk in the sea showed that the amount of corrosion *decreased with the thickness of the casting, and that from* $\frac{1}{10}$*th to* $\frac{4}{10}$*th inch in depth, in castings* 1 *inch thick, and about* $\frac{6}{10}$*th inch of wrought-iron, will be destroyed in a century in clear salt water.*[1]

*Examples of very rapid Decay.*—There are in my possession specimens which prove that with some kinds of iron the rate of oxidation in thick castings had been more rapid than in the samples employed in Mr. Mallett's experiments. In

[1] *Brit. Association Report*, 1839 and 1850.

1833 a cannon-ball, $4\frac{1}{2}$ inches diameter, was picked up on the eastern shore of Inchkeith island, in the Firth of Forth, at a place that was left dry two hours and a half before low water of spring tides. It was, therefore, not constantly immersed, but was only alternately wet and dry, a condition which is generally believed to retard materially the progress of decay. The shore at the place is gravelly, with rocks intervening, so that there was no peculiarity of soil that could have hastened chemical action. The external appearance of the ball is precisely that of any ordinary casting which had for a long time been exposed to atmospheric influence, indicating the presence of red carbonate in some parts, while in others there appears a smooth skin, possessing a certain degree of metallic lustre. The raised ring which had been formed by the edges of the mould is still quite apparent, and the radiated structure of the interior is also distinctly visible. But so thoroughly has the iron been changed, that the ball weighs only *one-fourth* of what it would had the metal remained sound. So perfect is the transmutation, that there cannot be detected, even in the centre, the slightest trace of unaltered metal. The whole forms an earthy substance, consisting, I believe, principally of carbonate of iron.

The preference which is now so frequently given to iron as a material, even in cases where a nearly indestructible substance ought, if possible, to be employed, makes it of some consequence to ascertain the probable date of the immersion of this cannon-ball, which there is every reason to believe from the following facts was not earlier than 1564.

The first use of cannon in warfare is commonly believed to have been at the battle of Cressy in 1346; but as it is known that balls of stone were first employed, it seems very improbable that well-formed balls of cast-iron were made

until long after that period. The account of the earliest military operations at Inchkeith that I have seen is given by Sir Robert Sibbald in his *History of Fife and Kinross,* who states that, in the reign of Elizabeth, its capture became a matter of keen contest; so much so, that the English had then a fleet of twenty-nine vessels anchored off the island. The remains of Queen Mary's fort, which was erected for her by the French, and which bears her initials, with the date 1564, may still be seen on its summit. There is therefore good reason for supposing that it was during those contests, *at soonest,* that the ball found its way into the sea. If this be so, it proves that $2\frac{1}{4}$ inches of cast-iron (the radius of the ball) became thoroughly oxidised in the space of not more than three centuries, which assigns for the kind of iron of which it was cast *upwards of $\frac{3}{4}$ inch to the century for balls $4\frac{1}{2}$ inches diameter,* and placed so as to be alternately wet and dry.

At the Bell Rock Lighthouse, which was completed in 1810, Mr. R. Stevenson directed cast-iron tramways, consisting of rails with open gratings between, and supported on standards to be fixed to the rock. Many of these gratings, which are *not* constantly immersed, are now decayed in different places, cavities having been formed on their upper surfaces fully half an inch deep, thus giving *one inch to the century* for castings an inch square. It is remarkable, however, that in some of the specimens of this grating which I have examined, the decay is principally confined to those parts where there have been air-holes in the metal. The rapid decay in these holes is probably occasioned by the water being retained in them after the tide has receded; and thus the increased action due to constant immersion is produced at that part of the casting. Where iron is to be exposed to

only periodic immersion, it therefore comes to be of especial importance that the castings should be not only free from air-holes, but should be of a perfectly regular and slightly rounded form, so as not to present hollows for the water to lodge in. One of the bars, however, which was quite free from air-holes, and presented no external appearance of decay, had its specific gravity reduced to 5.63, and its transverse strength reduced from 7409 to 4797 lbs. Another apparently sound specimen was reduced in strength from 4068 lbs. to 2352 lbs., *having lost nearly half its strength in about fifty years*; and I strongly suspect that all the gratings, however sound they may look, have suffered a great reduction of their strength.

Even although the instances of such rapid oxidation as have been adduced be of rare occurrence, yet the bare possibility of such a speedy decay should discourage the indiscriminate employment of iron in marine works. Where there is room for choice, neither cast nor malleable iron should be used as *principal* constituents of any structures which require to be so deeply submerged as to become difficult of inspection or repair. If even thick castings, and those not constantly immersed, decay so rapidly, what can be expected of the durability of malleable iron bolts and tie-bars which do not exceed an inch or two in diameter? And what reliance can be placed on the stability of deeply submerged structures retaining large quantities of rubble, the unity of which depends wholly on such perishable bonds?

## Dressing and Method of assembling Masonry in Sea-Works.

For localities where the exposure is not very great, and where cement cannot be procured, masonry consisting of separate blocks has still to be adopted.

The requirements of marine masonry are, in many respects, nearly the opposite of those for land architecture. What is wanted in sea-work of the ordinary kind, which neither consists of framed carpentry, nor has been rendered monolithic by the use of cement, is that each stone shall gravitate freely, and transmit its pressure unimpaired to those below it. If, therefore, a pier could be so constructed that, on the abstraction of a stone at the bottom, the whole vertical section of masonry resting upon it should at once sink, so as to fill up the void, the perfection of marine masonry would then be attained, because the lower courses would bear the unreduced weight of the upper, and would therefore be the less easily abstracted. The difficulty of pulling out any stone in such a work would then be proportional to its distance from the top of the wall. Whereas in land architecture, vertical bond is systematically preserved, and the stones are sometimes so lintelled over, or, to speak technically, so completely "*saved*" from the superincumbent pressure, that it is often easy to extract some of the lowest stones in the wall without endangering the stability of the upper courses. In land architecture, the whole structure is also greatly strengthened by the occasional insertion of long headers and stretchers, but in the sea, where each stone is assailed *per se*, the stability of any horizontal course, if equally exposed throughout, is measured by the stability of the *smallest* stone in that course. And, therefore, the more uniform the size of the materials in each horizontal section of the work the better, provided that the "secret-bond," or proper connection with the backing, is duly preserved. We must beware then of importing into marine engineering, as is too generally done, the laws and maxims of house-architecture, with its careful vertical bond, and its small but finely dressed face-stones. It matters not, indeed, how

rough the masonry of the *face-work* of a pier be, provided there are no protuberances large enough to offer material resistance to the jet of water in front of the wall; and we have already pointed out the valuable effects of keeping the beds rough. All the blocks should, however, *bed and joint* fairly on each other, and no face pinnings, or small *closers*, should on any account be allowed in the outer face-work. It is also of vital consequence, that the *backing* should not be slurred over, by being loosely assembled; but should, on the contrary, be carefully set, and regularly bonded with the face-work as the building proceeds. The *outside* of the *parapet*, though of smaller dimensions, should be similar in quality to the sea-wall, while its inside, from not being exposed to the wash of the sea, may be built of good heavy rubble. The whole parapet may, with advantage, be set in mortar.

*Roadway Pitching.*—From the risk of damage already referred to, it comes to be a difficult question to decide whether the *roadway pitching* should be built with very open joints, or be made altogether impervious to water. Mr. T. S. Hunter, in his report on the Wansbeck River, mentions the following instance of damage to the pitching at Granton: "A portion of the pitching, which had just been grouted previous to the storm, was completely doubled up like a sheet of paper, but after the grouting was removed, and the same stones set dry, they were never again disturbed." The safe course in most cases, where the sea-wall is built of dry masonry, is probably not to attempt the formation of an altogether impervious covering; but where the roadway is made impervious, the compressed air may be discharged through the mooring-pauls, which, for that purpose, should be made of cast-iron with perforations on the top.

The *quay-wall* requires no particular notice. Minard

recommends its thickness to be $\frac{4}{10}$ths of the height. The upper portions are sometimes set in mortar, but the rest is set dry. The *rubble hearting* should be free of earthy or clayey matter, or rock of a quality likely to crumble on exposure. Very large boulders ought not to be admitted, unless after being broken up, and when any of the stones are long and flat, they should be laid lengthways of the pier, and in no case, unless when the structure is of great width, should the stones be tipped in without being afterwards carefully assembled by the hand. In exposed situations or in narrow piers, the hearting, which may be regarded as the *backbone* of the work, should not only be carefully assembled, but the stones should be set hard on each other, so as to give a continuous bearing throughout the whole width of the work. The *rubble for breakwaters* is generally of a much larger size than for ordinary commercial piers. The *ratio of voids* in a cubic yard of rubble after being deposited depends of course on the kind of materials, and has been found to vary generally from about 4 to about 8 or even 9 cubic feet in each yard, equal to from $\frac{1}{6}$th to $\frac{1}{3}$d of increased cubic space in the breakwater.

*Settling of Rubble.*—The materials of breakwaters are liable to sink, to be crushed, and to be driven together by the waves. At Cherbourg, settlements of about 4 inches were observed to take place after a tempest. At Algiers, where the bottom is soft, the rubble sank 6.5 feet into the sand, and at Boyard 5232 cubic yards were required below the level of the bottom. According to the late Admiral Washington, the settlement at Cherbourg[1] averaged 18 inches in 22 feet, or *one-fourteenth* of the height. At Alderney it was found when the weight of the superstructure came upon the rubble base the settle-

[1] Minard, pp. 56, 59.

ment amounted to about one-twentieth of the height of the mound. The head, which was founded 24 feet below low water level, settled at least 6 feet in the mound.

*Edge Work.*—The method of assembling stones on edge, instead of on their beds, which was used in some old Scottish harbours and sea-walls, as at St. Andrews, Prestonpans, etc., deserves to be more generally known and adopted, from its greatly superior strength. Mr. Bremner of Wick propounded the opinion that—"If the walls are constructed on a (horizontal) angle of 25° to the sea, and the materials built on edge with 3 inches of slope to the foot perpendicular, they cannot retain any air, and the sea, running along a small portion of the building at one time, actually assists in forcing together the edge building." Although it amounts virtually to a condemnation of nearly all modern sea-work, yet I do not hesitate to assert that it is a great engineering error to assemble stones in exposed works in any other way than on their edges, and I extend this remark even to materials of ordinary thickness, although the advantage is most conspicuous where the materials are thin. Care must be taken, however, not to adopt this plan where there is any risk of heavy seas coming in a wrong direction, so as to strike the masonry on the overhanging side.

*Rhomboidal Form of Stones.*—The strength of the masonry of sea-walls might be materially increased if the stones were dressed to a rhomboidal form. This could be done without much trouble or expense if the quarriers were furnished with bevelled templates instead of square, for quarrying the blocks.

*Size of Materials.*—In absence of any rule for the weight of materials in a built wall, the following approximation is submitted rather for trial than as a guide: When W =

average weight of blocks in tons, and $d$ = length of fetch in miles, $W = .3 \sqrt{d}$.

*Treenailing.*—A most efficient method of temporarily increasing the stability of marine masonry, which may be adopted in places where the materials are of small size and of a soft texture, is to connect all the stones together by a system of dowelling or treenailing. Each block is thus secured to its neighbour by iron bolts or wooden pins let into the lying beds, or into both beds and joints. At the Eddystone and the Bell Rock lighthouses, the stones were not only secured by oaken treenails, but were also cut so as to dovetail into each other, and thus to render the mass practically monolithic. They were also further secured by vertical wedges. But these methods are attended by an expenditure which is warrantable only in peculiar works like those, where the loss of a single block during construction is certain to occasion great inconvenience and delay. Mr. Leslie used timber treenails largely at Arbroath and Kirkcaldy, where the stones employed were freestone. The holes were bored by means of machines made for the purpose, at far less expense than if the ordinary tedious process of hand "jumping" had been adopted.

*Portland Cement, Rubble, and Concrete.*—This most valuable material may be said to have, to a large extent, revolutionised harbour-building; for it admits of being employed in many different ways, and can, if due care be taken, be used with perfect confidence in all but exceptional cases. The following specification has been followed extensively by Messrs. Stevenson for harbour and other works:—

The cement is to be the best London-made Portland cement, to be had from makers to be approved by the engineers before being sent to the works. It is to be brought to the works direct from the manufacturer, and not bought through

an agent. The cement is to stand the following tests:—It is to be ground extremely fine, and is to weigh not less than 115 lbs. per bushel, and each cargo will, on its arrival at the contractor's store, and afterwards, be tested weekly in the following manner: The cement is to be made into small blocks, 1 inch square and 8 inches long. After being made, these blocks are to be immersed in water for seven days, and then tested by being placed on two supports, 6 inches apart, when they must stand the transverse strain produced by a weight of 75 lbs. placed in the centre. Slabs or cakes are also to be made and placed in water, and after immersion for twenty-four hours they are not to show any signs of cracking or any softness on the surface. The cement is to be tested before any of it is used, and, if it be found unsatisfactory, it must be at once removed from the work store. When a fresh consignment is received, it must be tested from four different bags, and it must also be tested weekly as the work proceeds, and the results forwarded to the engineers. The cement is to be tested at the expense of the contractor, and at the sight and to the satisfaction of the inspector.

The cement must be kept in a dry and well-ventilated storehouse, with wooden floor, and side walls, properly roofed in, and completely protected from the weather.

*Concrete.*—The concrete to be used to consist of 1 part of Portland cement, 3 of sand, and 5 of shingle or broken stones of such size as will pass through a 2½-inch ring, and these materials are to be thoroughly mixed with a proper quantity of pure water. After being deposited within the frames to a depth of 2 feet, rubble stones of angular shape are to be added, care being taken that all the stones are completely surrounded by concrete for a thickness of not less than 4 inches, and no stone must approach nearer the face of the walls than 9

inches. The wall to be brought up in successive layers until the required height is reached. All stones to be clean and quite free from seaweed or other vegetable matter likely to prevent the adhesion of the concrete. No concrete to be made during frost. The sand and gravel used must be sharp and clean, being perfectly free from clay or earthy matter. The proportions of cement to the other materials, of course, vary with the nature of the work to be executed.

*Mixers for Concrete.*—There are different kinds of machines by which the concrete is thoroughly mixed and a saving of cost effected. In that of Mr. Messent the number of revolutions to mix the concrete thoroughly is twelve. When making concrete by hand the materials are to be thoroughly mixed in a dry state by being twice turned over on a level platform, after which a proper quantity of water is to be added and the materials again turned over, care being taken that none of the water is allowed to escape.

*Blocks of Cement Rubble used at Wick.*—My friend Mr. Alan Brebner, who took charge of the arrangements for depositing blocks of cement rubble at Wick, has kindly drawn up the following particulars :—The large blocks constructed for the protection of the end of the breakwater having to be floated into their places by means of machinery placed upon lighters, were made in positions within the high-water mark, such as would permit of the lighters floating alongside of them at any tide. The range of spring-tides being only about 10 feet, sites were selected on the beach about 2 feet above the level of low-water spring-tides. The first operation was to prepare level beds for the timber platforms on which the blocks were built. The platforms measured 22 feet long and 16 feet broad each, and consisted of 4 cross-sleepers 12″ × 6″, bolted down to 12 stones, about 15 cwt. each, pre-

viously sunk into the beach and levelled. The sleepers were covered with 3-inch planking, jointed with Roman cement, driven close together, and then spiked down. Twelve platforms were constructed at a cost of about £20 each. The sides of the boxes were formed of 3-inch planks, secured at the corners by palm bolts and nuts, so as to admit of their easy removal after a block had been completed. The joints of the planks were slightly bevelled to the outside, leaving a wedge-shaped space, which was filled with Roman cement to exclude the water. The blocks were all 5 feet 6 inches high, and this height was made up in 6 widths of planking. Three widths of planking were put down, and filled, generally in one tide, the other three in the tide following, and the block completely finished and smoothed off in the third tide. The blocks, which weighed from 80 to 100 tons, consisted of one part of Portland cement to seven of small stones, sand, and gravel; they were not what is commonly termed built blocks, the whole of the stones being assembled by labourers only. The stone used was of a high specific gravity, and in pieces of from 10 to 80 lbs. weight.

In commencing the blocks a covering of stones was first laid over the bottom, care being taken that spaces nowhere less than one inch was left betwixt them. The cement, sand, and small gravel were made into a thinnish mortar, and conveyed into the box in wheelbarrows. The spaces betwixt the stones were completely filled, and a covering of 2 or 3 inches laid over them to form a bed for those to follow. A sufficient force of men was always employed to build a block half up in one tide, and before the water covered it a sheet of canvas was laid over it, and loaded with stones, to prevent the waves from acting on the cement until it had time to harden. Next tide the covering was removed and the block completed.

Near the four corners of the blocks boxes were inserted to form holes for the lifting bars. Those boxes rose one foot up into the blocks, and from that level tapered battens were carried up above the top, and withdrawn when the cement had set. Bars of iron 3 in. × 1 in. were built into the holes to prevent the lifting bars from cutting into the cement work. In two days after the blocks were finished the wood was stripped off them, and in eight days they were fit to be, and sometimes were, lifted from the platforms and built into the pier. A much smaller proportion of cement is generally used in making concrete blocks, but the unusually heavy seas in this situation required the blocks to be very strong.

*Lifting the Blocks.*—The machinery used for lifting and setting the blocks is shown in the diagrams Figs. 30 and 31, and consisted of two lighters, each capable of carrying 50 tons; on these were erected two strongly-trussed timber frames, tied and braced together, so as to preserve the lighters in a position parallel to each other. Two logs of greenheart timber rested on the trusses, and carried the brackets and pulleys for guiding the chains to the winches, and also the two upper pulleys of the lifting tackle. The blocks of concrete being of a considerable size, it was considered advisable to lift them by four points, to avoid the risk of breaking in the lifting, and also to distribute the load as much as possible over the floating structure. It was evident that a strain considerably more than what was due to the dead weight would be thrown upon the machinery by the motion of the waves, which sometimes broke over the seaward lighter, and fell on the top of the blocks betwixt them, adding greatly to the weight.

In order to secure an equal strain on each of the four lifting bars, which could not have been accomplished if four separate tackles had been employed, the chains were so

arranged that what is usually the standing part of the one tackle was made the hauling part of its neighbour, two pieces of chain thus forming the four sets of tackle. The arrangement will be readily understood by referring to the diagrams. This arrangement worked admirably, the friction in the pulleys being more than sufficient to provide against any want of

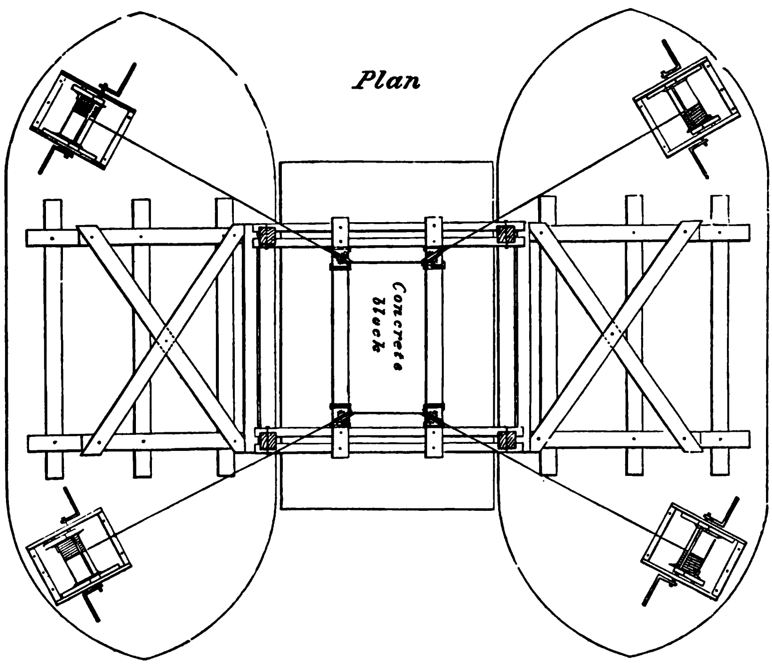



Fig. 30.

balance arising from the inaccurate placing of the lifting bars: it permitted the blocks being lowered into their places by means of breaks, which saved a great deal of time, and very much facilitated the setting. It also obviated all danger of the tackles breaking, from the work intended for two being

at any time suddenly thrown upon one. The tackles were worked by four powerful winches arranged as shown on the diagrams, and worked by four men. When a block was to be lifted the lighters were warped into the position shown in Fig. 30, the lifting bars inserted, and the winches set to work. In four or five minutes the block was clear of the ground, and was then warped out, and either deposited in deep water to make room for others being built or taken out and set in the work. To enable the blocks to be lowered down in a level position, the following expedient occurred to me, and

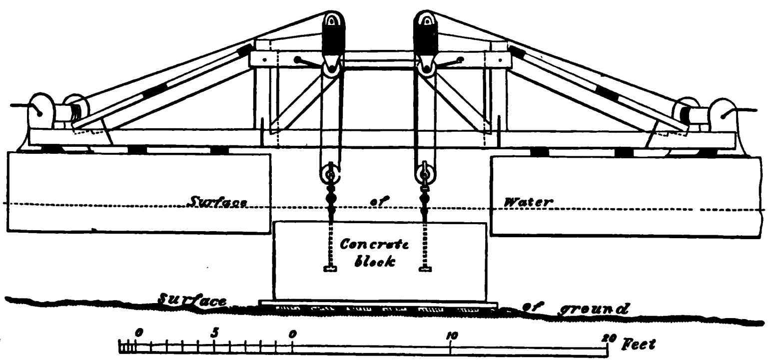



Fig. 31.

was adopted with satisfactory results:—The winches were numbered, and each had its number painted up in a position to be seen by the men working it, and also by the person directing the operations. After the tackles were mounted, and the chains wound upon the barrels of the crab winches, so that the whole was in the position shown by Fig. 31, white marks were drawn across the framing of the winches and large spur wheels on the end of the winding barrels. By this means the person in charge, who stood on a platform on the top of the framing, was enabled to observe, during the process

of lowering, the approach of the marks on the wheels to those on the framing, and thereby to adjust the level of the blocks at each revolution, and so ensure their reaching the bottom in that position. The lighters were steadied over the work by ropes attached to four mooring buoys laid down in the required positions. When nearly over their places the blocks were lowered to within a few feet of their beds, and when finally adjusted were lowered quickly to their places on a signal from a diver. The time taken to set a block depended greatly on the state of the sea. When quite smooth the operation was completed very quickly, at other times it would occupy about an hour.

The whole process, both of constructing the blocks under the tide level and floating them into their places, was perfectly successful, and was carried out without the slightest accident or breakage; the first block was lifted with perfect ease, and no change of any kind was required on the machinery as at first constructed.

*Voids between Blocks of Beton.*—"Sometimes," says Minard, "the workmen succeed in placing the blocks close together; but generally there are spaces between them of from $\frac{6}{10}$ths of a foot to 1.6 foot, and sometimes 2.6 feet. At Algiers, with blocks of 353 cubic feet (11.15 feet long × 6.56 broad) *thrown down on each other*, the voids are *one-third*."[1]

*Passing Concrete through Water.*—Sir John Hawkshaw[2] has passed concrete through 50 feet of water with perfect success. As far as his experience went the concrete set quite as well under these circumstances as when it was deposited in the open air. He has done this both in salt and fresh water. In passing concrete through water, he used a box containing about two cubic yards. When it reached the

[1] Minard, p. 58. [2] *Min. Civ. Eng.*, vol. xxiv. p. 170.

bottom a bolt was withdrawn and the concrete dropped out. At the harbour of Greenock, Messrs. Bell and Miller put in the low water foundation of the Albert Quay in concrete of Arden lime. Mr. Pascal, the engineer of the Marseilles works, formed in concrete the foundations of a beacon below low water at a submerged rock five miles from the shore. Mr. W. Parkes put in the foundations of the iron lighthouse in the Red Sea by means of a caisson, into which fluid concrete in bags was deposited. He thus describes the mode of construction:—"During this time some progress was made at the lighthouse works. The caisson of iron plates to enclose the concrete base had been set up, and about 200 tons of gravel had been deposited upon the reef, where it was exposed to a wash sufficient to remove some of its clayey particles, without carrying it out of reach. As soon as a sufficient quantity of gravel was accumulated, the process of depositing the concrete was commenced. As circumstances did not admit of the usual plan of depositing the concrete in the water in large masses from boxes, the following plan was substituted:—Sheets of tarred canvas were prepared, of such sizes as would fill up the spaces between the piles and allow two feet round each side to be turned up so as to form large shallow bags. The edges of the tarpaulin were then lashed to wooden rods, which were slung to the piles so as to allow the tarpaulin bag to float slackly on the surface of the water. Two or three hours before low water the work was commenced. The concrete was mixed in the lighters moored alongside the caisson, six measures of gravel being used with one measure of cement and a suitable quantity of water. The materials were thrown into the centre of the canvas bag, which gradually sank to the bottom (generally from one foot to two feet under water), and the bag was spread out evenly

over the whole area as it became filled. This was continued until the tide rose nearly to the level of the top of the deposited concrete, when the sides of the tarpaulin were drawn close down over the soft mass, and lashed tight. In this way blocks of from 6 to 14 tons were deposited without the material having been subjected in small quantities to the action of the water. The blocks were generally hard enough on the following day to allow of the exposed parts of the tarpaulin being cut away, and so complete was the set that casts of the cords and the edges of the tarpaulin were often sharply impressed upon the face of the concrete."

*Monolithic Structures of Cement, Concrete, or Rubble.*—In *Nature*, for September 1871, I suggested that lighthouses on rocks in the sea might in certain situations be constructed *wholly* of cement rubble. The advantages of this mode, or of gravel concrete, when used not in separate blocks but in *continuous building*, are the following:—1st, the dispensing with all squaring or dressing of materials. 2d, The suitableness for such works of any stone of hard quality, thus rendering it unnecessary to bring large materials from a distance, or to open quarries for ashlar. 3d, No powerful machinery is needed, as for moving or raising heavy materials. 4th, Saving in the levelling of the rocks for a foundation for the tower. 5th, The ease of landing on exposed rocks small fragments of stone, as compared with the landing of heavy and finely-dressed materials.

A beacon 13 feet high and 10 feet diameter was constructed under Messrs. Stevenson's directions in a very exposed situation near Isle Earraid, Argyleshire, which has stood perfectly for the last thirteen years.

The walls of harbours may also be constructed of continuous building, protected by temporary piling and close

planking, with the necessary protection of tarpaulins to protect the concrete from the wash of the rising tide. The lower part of the frames should be lined with old canvas or jute bagging for a height of 2 feet up the sides and extending 2 feet across the bottom all round. It should be tacked to the planking along the top and up the joints. The best mode of keeping out the water, as adopted by Mr. Balmer at the Duke of Richmond's harbour of Port Gordon, is to make a saw-draft in each plank, and to place a thin plate of iron between the planks. An example of this continuous or monolithic building is shown in Plate XXI.

*Concrete Cylinder Foundation.*—Mr. Deas of Glasgow has kindly furnished me with the subjoined particulars of the founding, by means of concrete cylinders, which he has adopted at the Plantation Quay, Glasgow, and which are shown on Plate XIX.

"The cylinders are made of concrete in sections 2 feet 6 inches deep. The concrete is thrown into wooden moulds placed on a carefully-levelled platform. A section of a group of three 12-feet cylinders measures nearly 17¾ cubic yards, and weighs about 33½ tons. To make the section easier lifted, it is made in segments of three and four pieces alternately, as shown in Plate XIX.: the heaviest of these segments is 11½ tons, and the lightest 9 tons 8 cwts. Mr. Milroy, the contractor for Plantation Quay Extension, makes three complete sections per day of ten hours. Of course this could be increased to any extent by the increasing of the plant. Mr. Milroy has one Blake's stone-breaker, and one Messent's concrete mixer, constantly at work to produce the above. About three weeks must elapse before the sections can be lifted after being made. The shoes are placed in the trench as near as possible at the level shown on

the drawing, and the whole height of cylinders is placed thereon before sinking is commenced. The cylinders are sunk by excavating the material, chiefly sand and gravel, from each well simultaneously, by means of Milroy's patent digger. The average working rate at which each group of three cylinders has been sunk is 2 feet 9 inches per day, including stoppages and delays of every kind. The greatest depth sunk in one day has been 13 feet 6 inches: 8 to 9 feet is a common amount during the first stage of sinking. As the sinking progresses each group requires to have weights placed on it to force it down, and frequently, by the time the bottom of the shoe reaches 50 feet below cope-level, a weight of nearly 600 tons of cast-iron rings has been stacked on its head. This quantity gives fully 5 cwt. per square foot of total outside surface of each group. To close up the junction of each two groups of cylinders, so as to prevent sand running through from behind, a red pine pole is driven, as shown on the plan, Plate XIX.

" *Concrete.*—The cylinders are of concrete, composed of one part by measure of cement to five of sand and gravel or broken whinstone, and the concrete used in the rubble building is of the same strength."

Mr. Messent has obligingly communicated the following notes as to the proportions of concrete :—

"For concrete blocks or ordinary walls, 6½ parts clean gravel or shingle, 2½ parts sand, and 1 part Portland cement.

"The Portland cement should weigh not less than 112 lbs. per striked bushel, lightly filled or sifted into the measure, and, if made into test-bricks, immersed in water as soon as they will hold together, should, after seven days' immersion, require at least 2½ cwt. to break each square inch of the breaking section of the brick.

"The usual area of the breaking section of test-brick is $1\frac{1}{2}'' \times 1\frac{1}{2}'' = 2\frac{1}{4}''$.

"For the above proportions $2\frac{1}{2}$ bushels of cement will be required for a cubic yard of concrete; and for the hand concrete-mixer, made to mix $\frac{1}{2}$-yard charges, the cement should be measured into bags containing $1\frac{1}{4}$ bushel—one bag being required for each charge; the hopper being the proper measure for the gravel and sand. Broken slag and broken bricks or granite spauls may be used instead of gravel or shingle.

"For large masses of concrete in foundations or quay walls the concrete may be made with two bushels of cement per cubic yard, or one bushel to each charge of hand-mixer; whilst in cases where extra strength is required, over openings, or to resist abrasion, the proportion of cement may be increased to three bushels per cubic yard. In each case the concrete may be cheapened without deterioration by placing largish stones in the fresh mixed concrete, care being taken that the stones are all surrounded by and separated from each other by concrete."

*Large Blocks of Concrete.*—Mr. B. B. Stoney has at Dublin deposited the largest blocks that have as yet been attempted.

"The blocks are at present used in the lower part of a quay wall, the total height of which is 42′ 10″, say 43 feet. Each block is laid 24 feet below L. W. of equinoctial springs, on a foundation levelled by means of a large diving bell, the chamber of which is 20 feet square, with a tube of wrought iron 3 feet in diameter, rising above high water. An air-lock at the top of this tube admits the workmen in and out, and several men can excavate inside at a time. The water surface inside the bell is quite calm in all weathers, and when the bell is resting on level ground the water is only about half-an-inch deep, so that it gives a plane surface of 400 square feet, which enables the bottom to be levelled with the greatest accuracy and facility. The bell weighs $80\frac{1}{2}$ tons. Each block is 27 feet high, 21′ 4″ wide at base, and 12 feet long in direction of wall, built on terra firma

of rubble, set in cement, mortar, and concrete. Each block contains nearly 5000 cubic feet, and weighs 350 tons; and when laid in place 12 lineal feet of the wall is finished at once up to ordinary low-water level. No cofferdam, staging, or pumping is required. The superstructure is built in the ordinary method by tide-work and is faced with granite ashlars for the ships to lie against. The blocks are built on land, and after ten weeks' drying are lifted by a floating shears, the barge or pontoon of which is 130 feet long and 48 feet wide, and of this 130 feet 30 form a tank at the aft end; and, when filled with water, this balances the weight of the block hanging from the shears at the other end. A block can be raised with the flood tide, and is generally set the following low water. The rising of the tide is not necessary, as the lift could be made in water with a constant level; but you can easily understand that a rapidly falling tide would not be desirable when lifting a block, as the floating shears sinks some feet under the weight of block and water, say 700 tons, and this, combined with a falling tide, would require the block to be lifted high up in the air. The blocks are laid touching each other, and the range is wonderfully accurate. A recess (vertical) is left in the side of each block, and into this vertical groove a lot of concrete is shot when the blocks are in place; this forms a key, and effectually stops up the little space (about half-an-inch) between block and block. Nearly five thousand feet in length of the North Wall have been built to September 1885, and the work is progressing very satisfactorily."

*Iron Concrete.*—Mr. Leslie has introduced at the Stranraer pier, which is constructed of timber, a concrete consisting of gravel and iron borings, which seems to have answered its purpose very well. Mr. John Howkins junior, who was the resident engineer, says (in a letter to Mr. Leslie, who has kindly communicated it to me):—

"The quantity of iron borings mixed with the hearting was

160 tons; and, taking the weight of gravel at 20 cubic feet to the ton, the proportion of borings to gravel, in weight, is 1 ton of the former to 17 of the latter, and the proportion in bulk 1 to 34,—assuming 10 cubic feet of iron borings to weigh 1 ton (which, however, I have not the means of ascertaining at present). The borings below low water were all thrown in by a person employed for that purpose, whose duty it was to scatter with a shovel a quantity as nearly proportionate as possible to the quantity of gravel which had been deposited at the side of the piling from the waggons. For the purpose of establishing that proportion, he had a box which was made capable of holding a quantity proportionate to the contents of a waggon. Above low water the gravel was thrown to the sides in thin layers, and the borings added alternately. In digging down at the end of the pier, where the gravel and borings had been acted upon by the sea for two and a half months only, I found the layers of borings caked in a hard mass, and particles of gravel and sand adhering to the sides of the layers; showing that the concretionary influence of the borings is extending, and will, in all probability, in course of time completely bind the intervening layers of gravel. I had also an opening made at the back of the slip coping, which has been filled in five or six months; and there the gravel, which is much coarser than at any other part (the sand and finer particles having been washed down and away by the sea), was very strongly coloured, and showed much the same appearance as at the end of the pier, only in a more decided degree. With regard to the coating of the timber, there is a decidedly rusty appearance on the outside of the piling, immediately above low-water mark, quite observable at a considerable distance; and, on a closer examination, the joints of the sheet piles are in a number of places seen to be giving forth that slimy discharge similar to what is so commonly observed in the neighbourhood of ironstone."

*Asphaltic Masonry and Concrete.*—I have tried at the island of Inchkeith some experimental masonry, which is cemented together with British asphalte. At the same time

the experiment was successfully tried of letting down, under the surface of low water, stones and hot asphalte placed in canvas bags, which were pressed down upon the irregular rocky bottom, so as to equalise it and render its surface ready for founding on. This substitute for mortar or cement in rubble and ashlar work seems capable of resisting the chemical action of salt water, for at Inchkeith it has stood for several years. Mr. Manley mentions that asphalte was proposed for harbour works in France, but that the risk of its decay prevented its adoption. He does not mention, however, whether any experiments were made in order to test its qualities.

*Carbonite Cement.*—Mr. H. C. Paterson, of Glasgow, has directed my attention to a new material for building and concrete, which plainly presents features of marked interest, the invention of Dr. George Hand Smith, of New York, a prominent American metallurgist. It is the result of a combination mainly of hydrocarbon of varying densities with clay, chalk, or gypsum, whereby concrete and all kinds of material for building purposes can be produced. The constituents are stated to be cheaper than those at present in use, as well as of a more durable character, being unaffected by frost or exposure, while they resist the action of the most powerful muriatic, sulphuric, and hydrochloric acids. It is further stated that the concrete can be made of any required density.

The following extracts from Dr. Smith's statement regarding this new material will be of interest to the engineer. One of the great recommendations of this cement is the fact of its being fit for use immediately after being manufactured. There is also claimed the further advantage that the blocks are capable of being fixed to each other

under water by an indestructible cement of great binding power, which is also prepared in the process of manufacturing the carbonite. The first process by absorption is thus described :—

"The first step in the process is the proper preparation of the vitally important carbon bath, which consists of a suitable tank or tanks to receive the chalk, etc., containing in a liquid state, insoluble, non-volatile or free carbon, suspended and combined with volatile hydrocarbons in the definite proportions desired. Other chemical substances are also added in moderate quantity, as experience dictates, to modify the action in view—such, for instance, as alumina, iron, etc.—although the relative action of the two forms of carbon is an ever-constant and essential feature. The volatile carbon becomes the vehicle for inducting the free carbon into the chalk, etc., conveying in their turn the other elements associated or combined with them. The volatile carbon, on removal, evaporates or is driven off, leaving the free carbon permanently fixed. The proportions of the carbon are determined by the hydrometer, easily insuring accuracy of result. The bath is kept hot by steam, or a grate. For some purposes it may be cold. It should always be quite liquid. Whatever chemical agents are employed to modify the action of the carbon bath, neither in quality or quantity do they unfavourably affect the question of profit.

"Into this bath, by a simple apparatus of an open iron bucket or crib, controlled by pulleys, a large amount of the clay, chalk, or plaster, first moulded or cut into the desired form, or in masses or blocks to be afterwards turned or cut into shape, is at once immersed, whereby it becomes rapidly charged with the carbonaceous mixture. By means of successive cribs, which are re-loaded and discharged in regular turn, the impregnation is rapidly effected. For some products the volatile hydrocarbon, etc., is driven off by the cooling of the same on removal from the bath; for others it is accomplished in a different manner, as next described."

The second process is by compression, of which Dr. Smith says :—

"In the manufacture of bricks, large blocks, waterproof for basements, docks, etc., where the shapes are plain and uniform, it is more economical to effect the moulding of the brick, drain pipes, etc., and the carbonisation, at one and the same time. Machines for this purpose are fully perfected, that will turn out from 5000 to 8000 bricks per day, and drain pipes in proportion.

"The carbonisation is effected by combining the raw or common clay with the carbonaceous solution in the ordinary hot mixer; thereby rapid action ensues, the confined vapours playing a part, the clay becoming more or less anhydrous, or giving up its combined water; its place being supplied by the elements from the solution. The excess of vapour may be saved and utilised as before mentioned. These carbonised products of clay or chalk, on cooling, would become hard; are immediately compressed into shape, becoming much harder by their condensation. They have afterwards simply to cool, when they are ready for use."

Dr. Smith's other process by compression is the following :—

"In this method, instead of combining the earthy constituents and the carbonaceous solution, while hot, they are simply mixed together cold, or nearly so, or treated by immersion, and then compressed into the forms required. They are afterwards allowed to remain for a short time in the drying chamber, the same as described above, whereby the same change occurs; the volatile carbon being saved for further use, while the solid elements are permanently fixed. Chalk in pieces for cutting, or in slabs for marble, may be thus treated without compression.

"The advantage of this method consists in the ability to modify the *quality* of the products, where it is desirable to retain a larger proportion of all elements contained in the solution, as

in making some kinds of brick and blocks, artificial marble from chalk, etc.

"In addition to bricks, waterproof blocks of the very best description may be prepared, of large size, from five to ten tons, without the use of power-presses, suitable for construction of docks, piers, embankments, reservoirs, tunnels, waterworks, cellars, and all subterranean works.

"The remarkable ability of a product that has never been burned, to resist high pressure, is shown by the experiments of Mr. Kirkaldy, one of the highest authorities, whose Report is appended, where samples indicated between 7000 and 8000 pounds to the square inch as the crushing test, or over 61 tons on a four-inch cube, or over 500 tons to the square foot.

"The following Table (Molesworth's Formulæ) gives comparative figures:—

| Materials. | Pressure per square inch. |
|---|---|
| Portland Cement | 1000 lbs. |
| Common Brick | 1500 „ |
| Portland Stone | 3700 „ |
| Sandstone | 5000 „ |
| Granite | 8000 „ |
| *Clay Carbonite* | 8000 „ |

"Repeated tests of my own have since ranged as high as 10,000 pounds to the square inch, according to the proportions and method employed. 8000 pounds may, therefore, be safely regarded as a fair average."

"Report of Tests made by Mr. David Kirkaldy on Carbonised Clay.

"'Results of Experiments to ascertain the resistance to a gradually increasing Thrusting Stress, of five cubes, received from Dr. Smith:—

| Test No. | Description. | Dimensions. Inches. | | Base Area. Square Inches. | Stress in pounds when | |
|---|---|---|---|---|---|---|
| | | | | | Cracked Slightly. | Crushed. Steelyard dropped. |
| H 1502 | Material . . . | 3.97 | 4.08 × 4.08 | 16.64 | 112,370 | 123,870 |
| 1504 | Do. . . . . | 3.58 | 4.09 × 3.98 | 16.27 | 105,840 | 115,860 |
| 1503 | Do. . . . . | 3.85 | 4.00 × 4.02 | 16.08 | 89,280 | 109,640 |
| 1501 | Do. . . . . | 4.12 | 4.04 × 4.10 | 16.56 | 99,840 | 104,980 |
| 1500 | Do. . . . . | 3.88 | 4.08 × 4.00 | 16.32 | 89,520 | 93,560 |
| ... | Mean . . . . | ...... | | 16.38 | 99,370 | 109,582 |
| ... | lbs. per square inch | ...... | | ... | 6.067 | 6690 |
| ... | Tons per square foot | ...... | | ... | 390.2 | 430.2 |

"'All bedded between pieces of pine three-eighths inch thick.'"

*Measurement of proportions of the materials for Concrete.* —Mr. J. F. Bateman has long employed the following mode of determining the relative proportions of the various kinds of material. The method was to take "any vessel, no matter of what dimensions, so that they were correctly known, and to fill it with as much gravel as it could be made to hold by shaking or beating it down—if gravel and sand were to be mixed, then by putting in afterwards as much sand as the vessel would hold in addition, and shaking that down amongst the gravel, the quantity of gravel and of sand being respectively measured as they were put into the vessel. When as much sand as possible had been shaken down, as much water was to be poured in as the vessel would hold; the quantity of water would then represent the lime required, the theory being that each particle of sand or gravel should be imbedded in or surrounded by a matrix of cement; and if the amalgamation of the materials were perfect, then the water which undoubtedly surrounded every particle would correctly re-

present the lime or cement to be used; but as such perfect amalgamation could not be expected, a somewhat larger quantity of cement than water was employed. By this rule a thoroughly cemented mass of concrete was obtained.[1]

*Mr. Bremner's Pontoons.*—The bold project of the late Mr. Bremner, of Wick, for putting in the foundations of low-water piers, merits notice. Mr. Bremner proposed to construct, in some adjoining place of shelter, enormous *pontoons* of timber, in which the under parts of the work were to be built, and afterwards floated, in favourable weather, to the desired spot, and carefully grounded. Such a plan might perhaps be found economical and suitable in some situations; but the great difficulty would be to fit the bottom of the pontoon to the irregularities of the ground on which it was to rest.

*Mr. Rendel's Method of Depositing the Pierres Perdues.*—The late Mr. Rendel introduced the improved and very valuable method of depositing the *pierres perdues* or rubble, which is frequently used in the construction of large breakwaters; this method he first employed at Millbay Pier, near Plymouth, in 1838, in a depth of 38 feet; and afterwards, on a still larger scale, in the construction of the breakwaters at Holyhead and Portland. The improvement consists in depositing the rough materials from stagings of timber, elevated a considerable height above high water. The stones are brought on the staging in waggons, through the bottoms of which they are discharged into the sea. The principle on which these stagings are designed is that of offering the smallest possible resistance to the sea, the under structure consisting of nothing more than single upright piles for supporting each roadway.

The late Mr. Rendel kindly communicated to me the

[1] *Min. Civ. Eng.*, vol. xxxvi. p. 242.

following description of his staging, in a letter which is still worthy of preservation as coming from the original proposer:—

"I use no timber braces of any kind, as these offer more resistance to the sea than strength to the staging. At Portland, however, where any accident would be a serious evil, owing to our employing convicts in the quarries, we stay the piles with iron guys, fixed to Mitchell's screw moorings, and also truss the outer piles in each row with iron rods. We also fix the piles in the ground with a screw. At Holyhead, however, we only attach to each pile boxes filled with small stones, for the purpose of getting them into a vertical position, and use no stays or guys of any kind. The superstructure consists simply of balks of timber, with rails laid on them to carry the waggons. The piles are placed in rows 30 feet apart, and the ease and certainty with which the staging is constructed is such that a length of 30 feet, including the screwing in of the piles, the laying down of the roadways, and all minor works necessary to make them fit to carry the waggons, never occupies more than one working day and a half, and often less. The length of the piles that we are now using varies from 84 to 90 feet, the depth of water at both Holyhead and Portland being about 11 fathoms.

"Of the strength of the stage you may judge from its carrying on each roadway as much as three waggons, weighing in the gross twelve tons each.

"The advantages of the staging are obvious. It contributes greatly to the consolidation of the stone; it makes a greater length of breakwater to be under construction at the same time; and it enables the deposits to be carried on without interruption, almost in the heaviest weather. As an instance of this, I may remark that my resident at Portland informs me that the waggons and locomotives were engaged yesterday at a time when such a sea was running that large bodies of spray were thrown 55 feet above the water-level. As a proof of the facilities which the stage affords for rapidity of construction, I should state that we have deposited this year at Holyhead, where free labour is employed,

nearly one million tons of stones. The loss from accidents to the stage is comparatively small on its first cost, and when spread over the cost of the whole works it is a mere trifle."

The works at Holyhead, after the death of Mr. Rendel in 1856, were carried out by Sir John Hawkshaw; and Mr. Harrison Hayter described them before the Institution of Civil Engineers, vol. xliv., from which the following particulars are taken. The total rubble stone deposited in the breakwater was 6,990,862 tons, the greatest deposit in one day being 5220 tons, and in one year 1,066,918 tons. The cost of quarrying and filling 1 ton of stone was as follows:—

| Quarrying. | Pence per ton. | |
|---|---|---|
| Powder for headings and shafts | 2.80 | |
| Driving | 1.74 | |
| Superintendence | 0.04 | |
| Total cost of quarrying | 4.58 | = 4.58 |
| **Filling.** | | |
| Wages of fillers and gangers | 2.11 | |
| Quarrymen blasting large stones | 0.78 | |
| Powder used by quarrymen | 0.12 | |
| Wages of carpenters, smiths, strikers, point-boys, tool-boys, brakesmen, drivers of horses, platelayers, and general labourers | 1.27 | |
| Superintendence | 0.11 | |
| Cost of filling waggons | 4.39 | = 4.39 |
| Total cost of stone per ton | | 8.97 |

The cost of the rubble deposited in place in rubble mound of breakwater was 2s. 3d. per ton, and 2s. 7d. a ton for the outer 2500 lineal feet. The cost of one *bay* of the north breakwater staging erected, in place in 50 feet depth at low water, was as follows:—

| | | | | | | |
|---|---|---|---|---|---|---|
| 3700 cubic feet of Quebec yellow pine at 2s. 2d. . . . . . | £400 | 16 | 8 | | | |
| 4 tons 10 cwt. of manufactured wrought-iron work at £22 . . . . | 99 | 0 | 0 | | | |
| 2 tons 10 cwt. of rails at £10 . . . | 25 | 0 | 0 | | | |
| | | | | £524 | 16 | 8 |
| Labour in preparing timber and erecting stage, including cost of fixing ironwork, etc., 3700 cubic feet at 4d. . . . . . . | | | | 61 | 13 | 4 |
| | | | | £586 | 10 | 0 |

*Greenheart Timber Staging.*—At Pulteneytown harbour works, as already stated, it was found that the piles of the staging for depositing the rubble required to be of greenheart timber; but even these were broken in large numbers. The piles were invariably broken by the waves at about the level of high water. It will be seen from the accompanying table, which is taken from a paper by Mr. Justen in the *Builder*,[1] that greenheart, irrespective of its valuable property of resisting to a great extent the worm, possesses such superior strength and specific gravity as to render it by far the best material that can be employed for such a purpose.

TABLE showing Specific Gravity of Different Timbers.

| | |
|---|---|
| Ironwood . . . | 1.210 |
| Greenheart . . . | 1.200 |
| Sabacue Wood . . . | 1.100 |
| Brazil Wood . . . | 1.100 |
| Oak . . . . | .885 |
| Beech . . . . | .852 |
| Ash . . . . | .854 |
| Elm . . . . | .800 |
| Fir . . . . | .657 |
| Cedar . . . . | .561 |

[1] Tables by Joseph Justen, on the properties of timber, republished in *Engineering Facts and Figures*, by A. B. Brown. Lond. and Edin., 1864, pp. 359, 364.

TABLE of Strength and Weight of Different Timbers.

| | Constant. | Weight per Cubic Foot in lbs. |
|---|---|---|
| Yellow Pine . . | 358.5 | 25.687 |
| Baltic Pine . . | 444. | 29.062 |
| Red Pine . | 467. | 33.437 |
| Ash . . . | 517.75 | 41.812 |
| English Elm . . | 592.25 | 37.312 |
| Pitch Pine . . | 629.00 | 45.750 |
| American Elm . . | 631.50 | 45.312 |
| American Oak . . | 653.50 | 44.875 |
| African Teak . . | 673.50 | 60.562 |
| Mora . . . | 691.00 | 71.250 |
| Sabacue . . . | 854.25 | 59.687 |
| African Oak . . | 869.50 | ... |
| Greenheart . . | 1079.50 | 69.750 |
| English Oak . . | | 53.312 |
| Indian Teak . . | | 38.125 |
| Ironwood . . | | 73.500 |
| English Larch . . | | 32.562 |

*Iron Lattice-Work.*—I have found reticulated framings, consisting of malleable iron bars, useful for protecting the masonry of piers above low water, where they can be *paid* over with hot pitch from time to time as required. The bars, which require very few attachments to the masonry, can be welded or riveted together so as to form large frames, having open meshes of from one square foot upwards; and if made with ring joints would form a sort of *chain net-work.* Iron lattice-work has been used in protecting the sloping surface of a weir in a river which is subject to sudden floods, as also in a sea-wall at Arbroath. The principle of the iron lattice-work is the combination of a large part of the strength which is due to a whole plate of metal, with a greatly reduced surface, thus giving a superabundant outlet for the escape of air and water.

# CHAPTER XI.

## ON THE EFFICACY OF TIDE AND FRESH WATER IN PRESERVING THE OUTFALL OF HARBOURS AND RIVERS.

**Pools and Shoals due to variations in the Flood-water Sectional Areas—Flood-water and Summer-water Sectional Areas inversely proportional to each other—Gravelly Rivers—Contraction of Estuaries—Relative Values of Salt and Fresh Water for Scouring—Tidal Guts—Allegation that greater Velocity of Flood-tide must cause Silting—Value of Tide Water—Abstraction of Fresh Water—Symmetrical Section—Forced Section—Abstraction of Fresh Water may occasion Deposits—Beneficial Action of Waves on Lower Reaches—Bars.**

THE commercial value of our harbours and navigable rivers is principally dependent on the depth of the channels which connect them with the ocean. It seems, therefore, scarcely possible to over-estimate the importance of ascertaining what is the principal agent that scours and preserves the depth of such channels, and what are the conditions under which that agent operates to the greatest advantage. Yet it is one of those subjects on which much difference of opinion prevails, and there is consequently a corresponding want of agreement among engineers as to the principles which should regulate the design of works for improving tidal channels. The engineering of rivers and estuaries has been very fully treated in Mr. D. Stevenson's *Canal and River Engineering.* The only part of the subject which requires notice here, as more especially belonging to harbours, is that of the relative values

of salt and fresh water as scouring agents, and I have to refer the reader for further information on this and all other subjects relating to River Engineering to Mr. Stevenson's Treatise.

*Pools and Shoals in Rivers above the influence of the Tide due respectively to Contractions and Expansions in the Flood-water Sectional Areas.*—It is unquestionably a fundamental law of hydrodynamics that by contracting a channel you secure a deeper track if the soil be so soft as to be removable by the increased velocity of the current.

I had lately occasion, with reference to a question of law, to inquire into the causes of the formation of certain pools and fords which existed in the upper parts of a river to which the tide had no access. The conclusion at which I arrived was that, where not due to differences in the nature of the soil, shallows were occasioned either by bends in the river, in which case, unless in very peculiar circumstances, where the velocities are very great and the curves very sharp, they are formed on the convex side of the stream, or else to enlargements of the flood-water channel; so that, where the summer-water area is small and the velocity great, the flood-water area will be large and the velocity small, and *vice versa.* Conversely, that deep pools were due either to bends, in which case they are formed on the concave side of the stream, or to contractions of the flood-water sectional area, owing to the banks above the summer-water level being high and steep. In other words, *where the stream has a straight course, and the soil is homogeneous, there is a constant relation subsisting between the flood-water and summer-water sectional areas, and these two are inversely proportional to each other.*

*In Gravelly Rivers the great leading features of Depth and Direction are due to the occasional action of very heavy Floods, and not to the river in its ordinary state.*—In rivers which pass

over heavy gravel, the bed, both as regards depth and direction, will depend upon great land floods, which are alone able to scoop out to a great depth heavy gravel and boulders. I believe that the river Spey in Morayshire still bears marked traces of the great Morayshire floods in 1829, when the discharge was greatest, or rather when the ratio subsisting between the sectional areas and the discharges was the greatest, and when the scour at the bottom would of course increase those ratios.

The greatest floods should therefore make the greatest excavations at some places and the greatest deposits at others, just as the relative magnitude of discharge and areas shall determine.

The pools formed by the greatest flood will not remain of the same depth, for the river under the influence of smaller floods carries along periodically certain sizes of gravel, washed down by rain from the land, in quantities inversely proportional to the cubes of the diameters of the gravel—to the density of the materials—and directly proportional to the duration and amount of the discharge of water. The first considerable flood after the greatest will not move the heaviest class of boulders which the greatest flood had no more than been able to move a very short distance; but gravel of lesser size will be carried down the steep slope at the upper end of the pools. When this gravel comes into the pool it will be in deep water, and rest on a comparatively level bottom, and not so likely, in such circumstances, to move, as during greater floods. The tendency of a succession of such floods is obviously, though very slowly, to restore the level of the pool to what it was before the occurrence of the greatest flood.

But these remarks apply only to what has been termed

the "river proper," to which the tide has no access. In such a case no changes in the alveus of the stream can possibly affect the amount of the scouring agent, which consists of rain from the uplands, and the produce of springs; and which amounts, less absorption and evaporation, *must* be passed through every section of the channel on its way to the sea.

*Contraction in an Estuary may reduce amount of scouring power.*—But the case is different with a tidal river or branch of the sea, in which, although a local contraction will undoubtedly produce an increased *local* depth, it does not follow that such contraction may not injuriously reduce the depth nearer the sea; for if water be excluded from the banks of the upper estuary, there is a risk that it may altogether cease to enter the estuary from the sea.

*Relative Values of Salt and Fresh Water as Scouring Agents.*—Some engineers (among whom was the late Mr. Robinson Palmer) have gone so far as to consider the fresh water the only efficient scouring power, while they regarded the tide water as rather an evil. In April 1812 the late Mr. Robert Stevenson discovered in the river Dee, at Aberdeen harbour, that when the salt water of the ocean enters even small estuaries during flood-tide, it does not, as had before been supposed, oppose and commingle, in ordinary states of the weather, with the outgoing fresh water; but from its superior density, as proved by the hydrometer, insinuates itself along the bottom of the channel, and raises the fresh water above it, which still continues its regular discharge outwards into the sea, in a film separate from the salt water. I have seen the flood-waters of the river Almond pass Granton harbour in a separate brown-coloured stream, and I have sailed through the flood-waters of the Dee, which tasted brackish at some miles off the coast near Aberdeen harbour. Father

Manuel Rodriguez, speaking of the river Amazon, says it "communicates to the sea a flavour, so that at 80 leagues within the sea its waters are seen and taste sweet, and in a semicircle of 100 leagues in circumference they form a gulf not the least degree brackish, so that sailors call it the fresh sea."[1] In 1817 the late Professor Fleming, in repeating at the Tay similar observations to those made at Aberdeen, found corroboration of Mr. Stevenson's result, and that even 18 miles from the river's mouth the specific gravity was greatest at the bottom. He further found that the marine vegetation *adhering to the bottom, though not appearing at higher levels*, also bore its testimony to the constancy of the operation of this law. He noticed that at Flisk, "and even farther up the river, the *Fucus vesiculosus* (the species commonly cut for making kelp) not only vegetates, but in its season appears in fructification at the bottom of the channel. But that which proves in a still more decisive manner the action of the inferior stratum of salt water at the place, is the growth of the coralline termed *Tubularia ramosa*, and another of a different genus, closely resembling the *Sertularia gelatinosa* of Pallas."

*Tidal Guts.*—Perhaps as obvious a proof as can be adduced of the independent and separate action of the flood-tide is the formation in the lower parts of estuaries of what are called *tidal guts*. These are subsidiary or lateral low-water tracks, having always their greatest width next the mouth of the river, and contracting gradually upwards. In many instances, as, for example, in the Tay and in Lough Foyle, these tidal guts, though often rivalling, and even exceeding, the depth of the main channel through which the fresh water passes, are *blind* channels, ending in a *cul de sac* at their upper ends.

[1] *El Maranam y Amazonas*, Madrid, 1684, p. 18.

No stronger proof than this need be adduced of the great power of the flood-tide in excavating and moulding for itself deep channels which are altogether separate from that which is occupied by the fresh water.

*Allegation that the greater Velocity of the Flood-tide which proceeds landwards must cause a Silting-up of the Estuary.*— Mr. Palmer stated that "the effect of the flowing tide in raising the bed of the river exceeds that of the ebbing tides, and hence we may conclude that the depth of the channel is entirely and exclusively dependent upon the water which is derived from the uplands." The question may certainly very properly be asked how it is that in any case where the flood-tide has a greater velocity than the ebb, it does not bring in more sand than the ebb takes out. At first sight one would certainly be led to infer that although the flood-tide no doubt excavates deep tracks in the lower reaches of navigations, yet in the upper parts of salt water *bays* into which no rivers discharge, and where there are no land freshes, it should cause accumulations. The only answer that I can think of is the fact that the flood-tide, in bringing up sand from the ocean, has to raise it from a lower to a higher level, or, in other words, has to work against gravity; while the ebb, in dragging the particles from a higher to a lower level, is assisted by gravity.

It is therefore quite in accordance with mechanical principles that the ebb, though having a less velocity, should, in pushing the particles down hill to the ocean, operate as much on the bed as the flood-tide with a greater velocity in pushing the particles up hill from the ocean. In estuaries where there is a large discharge of fresh water, the case is clear enough, because in these the ebb is assisted by the outgoing fresh water, which also, in some states of the weather,

largely interferes with the translating power landward of the flood-tide.

From these premises we may conclude that both the fresh and tide waters are useful in preserving the navigable depth. Were it otherwise we should find the very opposite of what is seen everywhere in nature. The lower down we go in an estuary we generally find the larger low-water sectional area; whereas, if the fresh water be the only scouring power, and the tide water an evil, we should find the greatest depth and the greatest sectional area in the "river proper."

*Value of the Tide Water which covers the Banks or fills the Side Creeks oj a Navigation.*—Some engineers, who do not dispute the efficacy of the tide water as a scouring power, are not prepared to admit that the water, which at high tide occupies the banks and side creeks of a navigation, is of much, or perhaps of any value. The difference of opinion which exists among engineers seems to arise from the want of any method of determining, by direct observations, whether or not such tidal water has in any case operated effectually as a scouring agent. The daily varying amounts of tidal water which are propelled into an estuary from the ocean; the ever-changing discharges of the land-waters, being sometimes very small and at others prodigiously increased in volume; and the heterogeneous nature of the materials forming the bed, which at different parts of the same river consists of gravel, sand, or mud, exhibiting an endless variety in the sizes and coherence of the particles—present an almost hopeless complexity for the mind to grapple with, or for even elaborate observations to unravel.

From a comparison made some years ago of different low-water sectional areas of river estuaries and of open bays in their state of nature, I remarked in the first edition of this

book, that in many estuaries and creeks *the low-water sectional areas seemed to increase directly as the quantities of tide water that passed landwards of such section lines.* By thus comparing the sectional area at any point with the area at a point a little farther down the estuary, we free the question from the difficulty of dealing with the unknown action of the freshes, which is nearly the same at both places, as well as of the ever-varying amount of the tides, which is also the same at each. We should therefore, where the bottom is of uniform consistency, find a progressive increase in the *low-water* sectional area, proportional to the progressive increase in the amount of tidal water as we approach the sea, because the amount of tidal water is always increasing, while the land-freshes in most rivers remain nearly the same, at least for short distances. It is not, however, asserted that the principle has been sufficiently established to admit of general application, nor is it probable that it can; but it is a convenient method of illustrating the beneficial influence which, in some estuaries at least, is exerted by the water which covers the banks at high tide.

Where $a\ a'\ a''$ are low-water sectional areas of the channel in approaching the sea, and $c\ c'$ are the intermediate *high*-water capacities, then

$$a'' = \frac{c'}{c}(a' - a) + a'.$$

The following are examples taken from the Tay below Newburgh, and from Belfast Lough :—

*River Tay.*

| Actual Capacities. | Capacities by Calculation. |
|---|---|
| 87,355 | 92,000 |
| 109,646 | 99,600 |
| 104,226 | 155,652 |
| Mean 100,409 | Mean 115,751 |

*Belfast Lough.*

| Actual Capacities. | Computed Capacities. |
| --- | --- |
| 242,651 | 243,000 |
| 318,208 | 304,000 |
| 367,913 | 319,000 |
| 333,721 | 387,000 |
| 453,623 | 463,000 |
| Mean 343,223 | Mean 343,200 |

In the narrow artificial channel of the Dee, Cheshire, the efficacy of a given quantity of tidal water was, as might have been expected, greater than in navigations which were left more nearly in a state of nature.

It must, therefore, be kept in view that what has been stated is merely of a general character, and is not to be regarded as of constant local application, for the value of a cubic yard of water depends on its level in the estuary. The following remarks by Mr. D. Stevenson should therefore be kept in view in dealing with individual cases.[1]

"It will readily be seen that the efficiency as a scour of a cubic yard of water filled and emptied by *every tide*, as compared with that of a cubic yard filled only *five times during every set of spring-tides*, is in the ratio of 730 to 144, not to mention the more effective scouring power of water discharged after half-ebb, as compared to a similar quantity discharged, for example, during the first hour after high water.

"The value of the water as a scour is therefore influenced both by its *volume* and by its *level*, and may be expressed as follows :—

[1] *Canal and River Engineering.*—A. & C. Black, Edinburgh, 1872.

$$S \propto V\,T,$$

where V = the volume or cubic feet of water space above the low-water level of the estuary.

T = the number of times it is filled by the tide throughout the year.

S = the effective scouring power.

"The only other consideration that should be kept in view is that of two spaces, V, V′, of equal capacity, and filled *every tide*, that which is lowest in position will be most effective in operating on the low-water channel. These values must of course be held applicable only to different conditions of the *same river* where the hardness of the bottom to be scoured and other circumstances remain unaltered."

### EFFICIENCY OF FRESH OR RIVER WATER AS A SCOURING AGENT, AND THE EVILS OF ABSTRACTING IT FROM A NAVIGATION WHERE THE BOTTOM IS SOFT.

*Abstraction of fresh water where the soil is soft will cause reduction of capacity of the alveus and diminution of the quantity of water that enters from the ocean.*—The evils of abstracting fresh or river water from a navigation are twofold. *First,* Directly, by the loss of this constant scouring power. *Second,* Indirectly, by the diminution of capacity of the alveus, which is produced by the rising of the bottom and sides consequent on the reduction of the fresh-water scour, so that the difference in amount of tidal water due to the decreased area of the alveus is wholly excluded from the navigation. It is obvious that the contraction of the alveus must reduce the quantity of water that used to come in from the sea; for if we suppose that a stream is diverted from its natural outfall, and allowed to discharge at another part of

the shore, the sectional area of the stream at any given place between high and low water will, if the shore be rocky, vary inversely with the fall of the beach at that place. But if the bottom be soft mud, the tendency of the stream will be to equalise its gradient by cutting (if the soil be homogeneous) a straight channel with a uniform gradient over the beach, due to the total distance between the high and low water margins divided by the rise of the tide. It is obvious, therefore, that after a sufficient time has elapsed, the stream will have cut an alveus in the mud of much larger sectional area than the sectional area occupied by its own *fresh* water. Nothing is more common than alvei, such as I have described, having at low water only a very small area occupied by the effluent fresh water.

Now, as the whole alveus is filled at high water, it follows that the comparatively trifling stream has secured an additional scouring agent from the sea, very much greater than is represented by the fresh-water sectional area multiplied by the distance between the high and low water margins, so that with the ebb-tide there is available for scouring purposes the constant fresh-water discharge, *plus* the whole salt-water contents of the alveus.

Even in narrow artificial cuts, such as the Dee at Chester, where the flood-tide comes in with a bore and the fresh-water current is reversed and sent landwards, the whole amount of fresh water impounded during the time of flood-tide is altogether insufficient to fill the estuary. Mr. D. Stevenson found the high-water capacity above Connah's quay to be about 220 millions of cubic feet, while the whole aggregate ordinary discharge of fresh water during flood amounts to only 3 or 4 millions of cubic feet. Hence we see that the fresh water in this case is vastly more efficacious indirectly than directly.

*Abstraction of fresh water, though it causes a reduction in capacity of alveus, does not necessarily reduce the depth in the channel.*—It does not follow, however, that the *bottom* will in all cases be raised by the abstraction of fresh water, although the capacity of the alveus is diminished. The bottom, for example, may have consisted of gravel of so large a size as to have resisted the eroding action of the original current, and therefore there may exist a gradient sufficient to generate a current which precludes the deposit of such light materials as the river brings down. If this be the case, instead of the *depth* being affected, it will only be the *breadth* that is changed. The reduction of the discharge will therefore alter the relation of breadth to depth without decreasing the depth.

*Symmetrical Section.*—Had the soil in the case which we have supposed been homogeneous—that is, had the soil of the bottom instead of being heavy gravel been the same as that of the sides—the symmetry of the section would have been preserved, and such a section may therefore be termed the *symmetrical section.*

*Forced or Artificial Section.*—The symmetrical may, however, not be the most suitable for the navigation, as it may be better to increase the depth at the expense of the breadth. But then, to reduce the scouring agent is not the proper way to effect this object, but the very reverse, for that would reduce the section without increasing the depth. If a *forced section* has to be substituted for the symmetrical section, the proper expedient is to erect stone walls at the sides, so as to destroy the homogeneity of the material forming the perimeter of the channel, and thus to alter the relation of depth to breadth.

*Abstraction of a portion of the fresh water which at present is capable of disturbing and rearranging the constituents of*

*any kind of soil, may occasion a greater deposit of the same, or of a finer kind of material, but not of a coarser.*—If what forms the existing bottom be the same as has been brought down by the present scouring agent, then any diminution of that agent will cause a new deposit of the same kind of material, or of a finer kind, but not of a coarser. This is clear, for if the original amount of scour was insufficient to lower any farther the former level of the bottom, it will be insufficient to move a heavier or coarser material. *If the reduced current be still able to move the materials stated in the first column of the Table,* then the deposit shown in the second column will take place; and if the current be still more reduced, then the order of succession in the third column becomes possible.

TABLE of Order of Deposit of Materials when Backwater is reduced.

| Nature of Present Uppermost Deposits. | Fresh Deposits that are certain. | Fresh Deposits that are possible. |
|---|---|---|
| If silt . . . | Silt. | |
| ,, mud . . . | Mud . . . . | Silt. |
| ,, sand . . . | Sand . . . . | Mud or silt. |
| ,, gravel . . . | Gravel . . . . | Sand, mud, or silt. |
| ,, boulders . . | Boulders . . . | Gravel or sand, or mud or silt. |

*Abstraction of the whole summer-water discharge.*—If the whole summer-water discharge of a land stream be diverted from its proper outfall for manufacturing or other purposes, a deposit, unless the water were absolutely clear, must take place throughout the whole navigation. But where the upper reaches are very narrow, and thus have a small flood-water sectional area, the deposit that will take place during summer droughts will be only temporary. Whenever the heavy winter freshes, which cannot be stored or diverted, descend from the uplands, the deposit that took

place during the droughts in those places where the flood-water sectional area is small, will, I believe, in most cases be removed, and the original area restored.

In the lower reaches, or at other parts where the flood-water sectional area is large, the result will be different. At the period of slack water of the tide, perfect stagnation must exist, and a greater deposit will take place on the flat banks than there would had there been even a small downward current to keep the water near the middle of the channel in motion, and to generate side currents, which would be found useful in reducing the tendency to deposit. After the tide has passed out, and the deposit on the upper parts of the flats has been subjected to the sun's rays and to the action of drying winds, it may attain a coherence so great as to resist the next winter floods, which act most powerfully in the *filum fluminis*—and not close up to the margin of the marsh land where this deposit has taken place.

*Beneficial Action of the Waves on the Lower Reaches.*—The permanent accumulation to which we have just referred will be greatest where there are projections of the land to afford shelter; but if waves get access from the ocean, or if the estuary be in itself wide enough to admit of the generation of waves of a foot or two in height, the deposit will be to a large extent broken up and removed during high winds.

*Bars.*—The cause of bars is not, as many writers affirm, the meeting of contrary littoral and river currents, but the heaping-up action of the waves, which thus form a kind of miniature under-water beach, whose position and height depend upon the relative forces of the waves and the outgoing river. The reader is referred to the works of Abbot Castelli,[1]

[1] *The Mensuration of Running Waters.* By Don Benedetto Castelli, Abbot of St. Benedetto Aloysio. Translated by Thomas Salusbury, Esq., London, 1661.

and to Mr. D. Stevenson's *Canal and River Engineering*. The obvious cure, then, is to shelter the bar by breakwaters, which will reduce the height of the waves. In order to proportion aright the breadth of entrance to the interior breadth, the formula for the reductive power given at page 165 applies.

One of the most successful examples of deepening a bar, by artificial means, is that of the Port of Dublin. Mr. B. B. Stoney says sixty years ago the bar, which consisted of hard sand, extending in a curved direction about half a mile east of Poolbey lighthouse, had only about 6 feet of water on it. At this time the North Bull Wall did not exist, but as soon as it was built the large volume of water flowing and ebbing over the 2500 acres which were inclosed between it and the Pigeon-House Wall was confined in direction and augmented in velocity, so that it impinged against the bar and scoured it away to its present depth of about 16 feet at low water, giving a depth of 28 feet at high water springs, and this is still gradually improving.

At the Tyne, by the erection of piers at its mouth, combined with dredging and other improvements in training the upper reaches of the estuary, an increased depth over the bar of 14 feet has resulted. This increased depth has led to the Tyne being used as a harbour of refuge, for during the year 1881 no fewer than 515 vessels, bound to other ports, found shelter within the piers, in addition to a large number of loaded vessels put back for shelter after leaving the Tyne, no account of which had been kept.

The works of improvement carried out at the Tees by Mr. John Fowler, consisting of two breakwaters, the north extending for a distance of 1133 yards and the south for a distance of about 4700 yards, into a depth of 30 feet at low water, constructed on either side of the entrance—the training

of the river by low walls, and the removal, by blasting, of a large area of rock which impeded the channel—have resulted in an additional depth of upwards of 14 feet. A section of the south breakwater is shown in Plate VIII. In 1863 the bar had a depth at low water of only 3 feet 4 inches; now there is a depth of 17 feet 6 inches. No dredging has been done on the bar or near it. The tonnage of vessels using the Tees in 1863 was 525,452, while during 1882 it had risen to 1,521,281 tons; the average tonnage of vessels in 1863 being 108 tons, and in 1882 it had risen to 256 tons. An outward-bound steamer of 4000 tons can now proceed safely to sea at high water of spring-tides.

# CHAPTER XII.

## ON THE PRINCIPAL CAUSES OF SILTING IN ESTUARIES.

**Deposits caused by Training Walls—Evils of Loss of Tidal Water—Features favourable to Production of Silt—Limit of Erection of Training Walls—Features favourable to Deposit at the Mersey—Allegation that no Deposit has followed Erection of Walls in Rivers—Loss of Scouring Power—Abstraction of Tidal Water at the Tay—Truth of Principles advocated.**

So long as a tidal river runs in a narrow channel, bounded by high solid equidistant banks, the axis of such river will be constantly parallel to its banks. But if the banks open out seawards, so as to form a wide tidal estuary, the river, while in a state of nature, will be liable to great changes in its direction, and will stray successively from one side of the estuary to the other, in consequence of the presence, it may be, of very slight deflecting causes, such as small deposits of sand or silt, which naturally form wherever the estuary is of unusual breadth. Much tidal energy is lost in such wide estuaries when the soil is soft and is continually wasted by the operation of what is called "fretting," or the eroding of the sides of the channel, occasioned by the frequent changes that take place in the direction of the stream, so that, after a certain lapse of time, every particle of sand that lay in the estuary must have been turned over by the current, which is amply proved by the fact stated that the channel works its way across from one side to the other, thus occupying in succession every position in the estuary.

In consequence of this great waste of energy in wide

estuaries, the navigable channel is always shallow, and hence the principal remedial works which are generally employed are what are called *training walls,* which confine and fix the course of the stream in one given direction, and protect the sides of the channel from erosion. In this way the first of the flood-tide and last of the ebb are so guided as to act conjointly with the land freshets in the same fixed channel, and so all further meandering of the stream is prevented and a greater depth of water is permanently secured.

In 1827, my late father, Mr. Robert Stevenson, when consulted as to the river Tees, objected to jetties or groins projecting from the shore at right angles to the current, and preferred to face the banks with stones; and in 1836 low training walls, placed parallel to the stream, without jetties, were first proposed for the Clyde, near Dumbarton, by the late Mr. James Walker; but the first river passing through an extensive estuary of sandbanks which was treated comprehensively throughout its whole extent by steam dredging and low training walls was the Ribble, where, on the suggestion of Mr. David Stevenson in 1840, low training walls were adopted, and eighteen miles of walling have been made there; and the uniform practice of Messrs. Stevenson has ever since been the same,—to make the walls parallel to the stream, and no higher than was found just sufficient, in each case, to direct the first of the flood and the last of the ebb-tide, and to contain the land freshes, for which a height of about three feet above low water has been generally found suitable.

One of the objects of the following remarks is to show that although training walls, in such wide estuaries, are generally highly successful in producing local improvement, it must not be hastily supposed that they are always unobjectionable; for in certain rivers having wide estuaries,

much matter in suspension, and shallow bars at their entrances, with existing ports near the sea dependent on the present depth being maintained, training walls ought not, in my opinion, to be employed. In the course of considering this very important subject in connection with the Liverpool and Manchester Ship Canal Scheme, as originally proposed to be carried out, and which gave rise to so much opposing evidence before Parliamentary Committees, I was led to the conclusion that the propriety of employing training walls in any river must be held to be in all cases dependent upon the existence or non-existence of certain natural features in the river.

*Deposits caused by Training Walls.*—It seems to be an invariable law that accretion will take place after a sandy or muddy river, having rapid tides, has been trained by walls in one fixed direction, when passing through a wide land-locked estuary; or, as stated in Mr. David Stevenson's *Canal and River Engineering*, p. 305, "Another effect of fixing a channel in the manner recommended is to form one permanent navigable track; and the banks on either side, being no longer subject to the periodical inroads of the river or tides, gradually rise in elevation until they are capable of producing vegetation, and ultimately become what are termed marsh lands."

It has recently been suggested by Mr. Leader Williams that the walls for the Mersey should not be raised above the surface of the sandbanks at all. This, I believe, will be found insufficient for the purpose of guiding the currents; but even though the channel could be so controlled, the effect of fixing the channel in one direction, in whatever way effected, would still be to restrict the passage of the strongest tidal currents to within the one narrow channel, hence reduction of velocity must take place at the sides of the estuary, and deposit must consequently ensue. This action

is thus described by Captain Calver[1]:—"We learn from the fourth fundamental law of running water, that 'the velocity of a stream is in proportion to the square root of the depth,' or (what will answer our purpose as well) the greater the depth, the greater the velocity. Hence it follows, that as the greatest depth would *always* be outside or between the training walls, so there would be the greatest velocity; and arguing from analogy, we can be at no loss in understanding that during the whole time of their submergence the walls would determine above them well-defined boundaries between the strong current of the channel and the weaker current of the flat; the latter gradually decreasing with the decrease of depth from the walls to the shore. The whole of the filaments of the current, in short, would be brought into a series of gentle curves harmonising with the general direction of the walls; and instead of being stopped and thrown off, thus impairing the combined effect, they would glide gently by with the least interruption possible. . . . The same relative movements reversed would take place upon the ebb; in either case the amount due to the sides of the tidal basin would be given off or received without disturbance, while the flats, being smooth and sloping, would offer nothing to take hold of, and entangle the current." The land floods and the residuum of the ebbing tides will be wholly confined to the new channel, and will therefore have no longer any effect in keeping down the sandbanks of the estuary (where comparative quiesence will be established), and removing the deposits brought in by the flood-tide. But further, the practical proof of these obvious deductions from hydrodynamic principles is, that deposits do not stop at the level of the top of the walls, but as a matter of fact rise far higher, as will

[1] *Improvement of Tidal Rivers*, 1853, p. 67.

afterwards be shown. One effect of training walls is therefore to convert what was formerly a receptacle for tidal water into dry land, provided only there exists a considerable amount of silt or sand in mechanical suspension in the flowing water. The direct effect of the deposit of this matter in suspension is therefore to chase away water from those parts of the estuary where silting takes place; and unless some other receptacle be provided, the water which has been so displaced will cease altogether from coming into the river from the sea.

*Evils of Loss of Tidal Water.*—Now, it has been held by almost all maritime engineers, both present and of earlier date, such as Telford, Rennie, R. Stevenson, Walker, Rendel, that if the water that enters from the sea be reduced in quantity, the low-water sectional area at the mouth of the river will also be reduced; so that, if the amount of water displaced be sufficiently great, the channel will shut up altogether, and the navigation be ruined. For example, in 1626, at Ostend, an embankment was made which excluded tide-water, when the harbour began to silt up, till the channel was only 1 mètre deep. In 1662 a cut was made in the embankment, and in 1698 the channel was from 13 to 17 mètres deep. This cut was closed in 1700, and complaints began to be made in 1716, and in 1720 the channel was almost closed. Again, at the harbour of Rye, extensive marshes covered by the tide were embanked by the riparian proprietors, and resulted in the channel being nearly obliterated. But in 1812 a very high tide destroyed one of the dams, after which vessels drawing 16 feet were able to get up to the town.

It is fortunate, however, that while the action of training walls tends to exclude water from the sea by causing accretion behind them, it also causes, on the other hand, precisely the opposite effect by enlarging and deepening the main

channel of the river between the walls, so that the ultimate result of their employment must be in each case determined by comparing the relative amounts of those two + and — quantities. If, for example, the waters of a navigation were absolutely free from matter in suspension, then walls would, from their deepening and enlarging the alveus of the improved navigable channel, be wholly beneficial, and the same will hold true even where there is matter in suspension if the estuary is of very small area; because, although the deposit may reach the level of high-water spring-tides, and the estuary be converted into grass-grown land at that level, yet, the area of the whole sheltered estuary being small, the total quantity of silt will not be so great as the increased amount of tide water that comes up the enlarged navigable channel between the training walls. But if, on the other hand, the land-locked portion of the estuary be of very large area, the total deposit may not only far more than counterbalance the additional water passing up the improved channel, but leave so little space for the reception of tidal water, that the amount of scouring water that can, in future, come in from the sea, will be insufficient any longer to keep open either the bar or the lower channels of the navigation.

*Physical Features which favour the Production of Silt, etc.*—If this represents the true view of the case, it becomes of great importance to ascertain what are those physical features that are favourable to the production and deposit of silt, and which, where they exist in any river, render it more or less dangerous to resort to training walls as a means of improving its navigation.

I may add that, so far as I am aware, no attention has hitherto been given to the connection between those physical peculiarities and the propriety of employing training walls

as a means of improvement; and it was only when considering the Manchester Canal question that I was first led to the conclusions about to be stated. The following are the natural features which tend to the formation or deposit of loose materials, and which are therefore more or less dangerous to any navigation where the currents are to be fixed in one direction by training walls in a wide estuary:—

I. *High Tides.*—Where the rise of tide is high, because, if there be matter in suspension in the sea (due to the action of the waves on the bottom when they reach shoal water) the higher the tidal column which enters the river the greater will be the amount of solid matter, for deposit, that will be brought in.

II. *Rapid Tidal Currents.*—Where the velocities of the flood-tide currents are great, because the larger will be the amount of sandy and silty matter that will be disturbed and carried up the river.

III. *Fretting.*—Where the river, in altering its direction through a wide estuary, removes from time to time large quantities of silt and sand.

IV. *Tidal Bore.*—Where there is a tidal bore with a cresting or breaking head, which, from its necessarily acting in shallow water, and with a very high velocity, greatly cuts up the bottom and sides of the channel, so as to set free a large amount of matter.

V. *Bars.*—Where there is a bar, or where there are extensive sandbanks with heavy breaking waves at the entrance to the navigation; because, as the depth is always shoaler there than at other places, and the disturbance of the breaking waves greater, very large quantities of matter are set loose, which will be carried into the estuary by the flood-tide, so that a bar and the adjoining sea-shores may be re-

garded as natural *silt producers*, which never fail to produce a constant and large supply of matter for deposit.

VI. *Wide Land-locked Estuaries.*—Where there is an extensive land-locked estuary, protected from the disturbing action of the sea waves, because from its large capacity it will, when sheltered by training walls, form a large sheet of water more or less stagnant, and therefore favourable for the deposition of any sand or silt which may be in suspension in the water.

*Natural Limit of Erection of Walls.*—A great evil must also be stated here, viz., where, from local peculiarities, it is impracticable to extend the training walls down to the open sea, or farther seawards, in the form of breakwaters, so as to shelter the bar; because the only known expedients for counteracting or modifying the evil of the reduced amount of tidal scouring-power produced by accretion is by concentrating, on the lower channels, what still remains of the reduced scouring-power, so as to enable it to act to the best advantage, or else by breakwaters in deep water to shelter from the waves, and thus to annihilate the bar, and so stop the further production of silt.

In order to illustrate the bearing of the above remarks, I have to state that Messrs. Stevenson, in the course of their practice, embracing the improvement of eleven navigations, have carried out designs for improving only five of these by means of training walls, two of which had gravelly bottoms and pure water, and where, of course, no accretion took place; but in the other three, which passed through soft soil, the erection of walls produced certain amounts of accretion in all their estuaries. These sandy rivers were the Nith below Dumfries, the Lune below Lancaster, and the Ribble below Preston.

*Deposits in River Nith.*—The river Nith extends between the town of Dumfries and the Solway Firth, and the only remedial work that was carried out was a low training wall 3 feet above low-water, without having recourse to any dredging of the bottom.

From a survey, which I had made in March 1884, it appeared that the deposit behind the wall had already reached the grass level, which is about that of high-water neaps, and much of it is now considerably higher than that level, being in some places 9 feet higher than the top of the wall. There are at present 250 to 300 acres of grass-grown land, which have formed since the survey of 1860, and the accretion since the completion of the works now amounts to 3,192,970 cubic yards of sand.

*Deposits in River Lune.*—Messrs. Stevenson were employed by the Lords of the Admiralty in 1848 to expend a certain sum of money on the improvement of the navigation of the Lune up to Lancaster, and low training walls 3 feet above low water were adopted, but in this case combined with dredging operations.

With the sanction of the Admiralty a series of sections of the estuary were made within two years after the completion of the works, from which it appeared that the estuary behind the western wall had at that time silted up to an average height of 4½ feet, giving a deposit of 3,000,000 of cubic yards of sand.

Although this very considerable amount of accretion had taken place, it did not at that date exceed the amount of the additional water admitted from the sea through the deepened navigable channel up to Lancaster, so that up to that date no more water had been excluded from the estuary than had been otherwise admitted by the improved navigable channel.

In February 1884, or thirty-four years after the works were finished, another survey was made, showing three very important results—(1) that the process of accretion had not stopped at the period of the former survey; (2) that it had continued to go on, and has done so, till the banks have now risen generally to the level at which grass begins to grow. (3) The deposit in some places is now as much as 10 feet deep, and has risen as much as 9 feet above the top of the wall. This silting action has also extended over a much larger area of the estuary than in 1838, though these parts have not yet attained the grass level.

There have also been formed, since the survey of 1838, 230 acres additional of solid land, now all covered with grass, and the accretion amounts to about 5,536,960 cubic yards.

It must here be noted that there never was any intention of reclaiming land by the works, and that in point of fact no part of the grass-grown surface was ever protected by any inclosing or cross walls.

Nothing, in short, was done here, any more than at the Nith, than the erection of training walls *parallel* to the new channel, and these were only three feet in height above low-water level, or just the minimum height which was found necessary for guiding the tide currents and land freshets.

*Deposits in River Ribble.*—The works adopted in this case were, on Mr. David Stevenson's suggestion, low training walls, now extending to about 18 miles in length, steam dredging, and the removal of rock from the bed of the channel. Up to the present time accretion has taken place to such an extent that about 5000 acres of land are now grassed over, and a large extent is being covered, though not yet to the grass level, and none of these reclamations were

artificially embanked until the deposits had become so high as to have become grassed over by natural means.

While it is manifest that the effect of such large deposits in these rivers must necessarily have been a considerable loss of tidal water by displacement, it must not be forgotten, on the other hand, that additional tidal water was at the same time admitted by the scouring and enlargement of the improved navigable channels. But, besides this, and what was most of all required, there being no large ports to maintain in the lower estuary, the following improvements in the depth of water and in the action of the tides were effected in the upper reaches of these rivers. At the Nith there was an additional depth of 2 feet, with a considerable acceleration of the flood-tide up to Dumfries; at the Lune an additional depth of 4 feet, and an acceleration of the flood-tide of 1½ hour, up to the quays of Lancaster; at the Ribble an additional depth of from 7 to 8 feet, and an acceleration of the flood-tide of one hour, up to Preston. Thus the improvements effected on the upper channel removed all the impediments complained of as obstructing the navigation of those rivers, while any loss of scouring-power that may have occurred could only affect places where, from the greater natural depth of water, it produced no visible evil, but where, if it had, that evil could have been obviated by extending the walls towards the sea, where the scouring-power, though reduced in amount, would have been concentrated so as to be more effective than it was before the works were carried out. But if these rivers had possessed estuaries as wide as the Mersey, instead of having been, on the whole, much improved, they would as certainly have been ruined.

We have next to inquire whether any and to what extent the aforementioned general features of danger are to

be found in the Nith, Lune, and Ribble, so as to help us to judge in how far deposits may be expected to take place in the Mersey if training walls are ever employed in that estuary.

Taking the aforementioned physical characteristics in the same order as originally stated, we find—

1. *Rise of Tide.*—That the rise of tide at the river Nith at ordinary springs is 28 feet; at the Lune 27½ feet; and at the Ribble 24 feet; from which it appears that silting to the grass-line level may take place where the rise of tide is only 24 feet.

2. *Velocity of Currents.*—The maximum velocity of the tidal current at the Lune is 5½ miles per hour; from which it appears that silting up to grass level may take place where the tidal current reaches a velocity of 5½ miles per hour.

3. *Tidal Bore.*—There was a very rapid bore with a cresting head at the Nith, but none either at the Lune or Ribble; from which it appears that silting up to the grass level may take place though there is no bore.

4. *Bars.*—There is no bar at the mouth of the Nith, but there is what perhaps may be regarded as a bar at the Lune; and there is certainly one at the mouth of the Ribble; from which it appears that silting to grass level may take place in rivers where there is no bar.

5. *Fretting.*—Before the improvement of the Lune, Nith, and Ribble, much sand was from time to time removed by alterations in the widest parts of their estuaries.

6. *Amount of Deposit depends on Width of Estuary.*—At the Nith, Lune, and Ribble, the estuaries form receptacles for deposit, their widths being respectively 1330 yards at the Nith, 1330 at the Lune, and 4400 at the Ribble, in all of which silting has taken place fully up to the grass level, so

that the ultimate quantities of silt must obviously vary with the widths of the estuaries.

7. *Approximate Amount of Matter in Mechanical Suspension.*—At the Nith there were found 3·68 cubic inches per cubic yard in mechanical suspension, and at the Lune 74·84 cubic inches per cubic yard; from which it appears that formidable deposits may in the course of 24 years be found where the proportion of matter in suspension is only 3·68 cubic inches per cubic yard.

*General Results.*—It thus appears that the estuary of a river may be silted up to grass level though the rise of tide is only 24 feet, and the tidal velocity is only 5½ miles per hour, where there is no bore or no bar (perhaps where there is neither), and where the proportion of matter in mechanical suspension is only 3·68 cubic inches per cubic yard.

*Physical Features favourable to Deposits at the Mersey.*—Applying these facts to the case of the Mersey, we find that the rise of tide is 31 feet, or 7 feet higher than at the Ribble. The tidal current is 7 miles per hour, or 1½ mile per hour more than at the Lune. There is a rapid bore with a cresting head. There is also a bar exposed to a heavy breaking sea, while there is none at the Nith; a large estuary 5200 yards wide and perfectly land-locked; and 33 cubic inches per cubic yard of matter in mechanical suspension, or 29·32 cubic inches more than at the Nith. There is also from time to time much sand removed from the widest part of the estuary by fretting.

It is obvious, therefore, that accretion up to the grass level cannot but be expected to follow the construction of a trained channel in the Mersey, inasmuch as all the six physical characteristics which are favourable to accretion are found in that river, which is true of none of the others;

while in nearly every case those dangerous characteristics are far more strongly marked than in any of the other rivers where the accretions occasioned by the works have now risen up to the grass level.

*Allegation that no Deposit has followed the erection of Training Walls at other Rivers.*—It has, however, been strongly asserted that no deposit has ever taken place in the rivers Clyde, Tyne, and Tees, although training walls have been in existence for many years in these rivers.

It is not surprising that the introduction of training walls has not produced deposit in all rivers, for the fact seems just as certain, on physical grounds, that they will not produce accretion in some rivers as that they must produce it in others. It is essential that before accretion can take place there must be matter in suspension, or, in other words, there must in some part of the river be water in such rapid motion as to break up and move the materials of the bottom and sides of the channel, while at some other part of the river there must be such retardations of the velocity of the water as to cause the deposit of the matter in suspension, and besides this a receptacle sufficiently large to contain the matter, and sufficiently sheltered from waves and currents to retain it after deposit. The essential difference between the two classes of rivers to be considered may be succinctly illustrated by one consideration: The mean rise of tide at the Cheshire Dee, the Mersey, the Ribble, the Lune, and the Nith, is 28 feet; while the mean rise of the Clyde, the Tyne, and the Tees is only 12·8 feet, or less than one-half of the former.

*The Clyde.*—My firm having for the last twelve years acted as engineers to the Clyde Lighthouses Trustees—the conservators of the lower estuary of that river—and having during that time been engaged in conducting very extensive

dredging operations on the lower estuary of the Clyde, I am necessarily very well acquainted with its peculiarities, and can state that there is only one point of resemblance of any consequence between that river and the Mersey, viz. that the lower land-locked estuary of the Clyde is about the same width as that of the widest part of the Mersey below Halehead, although there is no contraction below as at the Narrows in the Mersey. But then no training walls have ever been erected for guiding the channel through this wide estuary, so that we have no experience whatever on the subject. The walls which do exist in the Clyde are mainly in the upper part of the river, where the navigable channel is only about 400 feet wide, and where there is no space left for silting to take place between these walls and the land.

With the one exception of the wide estuary to which I have referred, none of the characteristics which are favourable to deposit have been found to exist in the Clyde, as I shall now show.

The rise of tide in the Clyde is only 10½ feet, against 30 feet at the Mersey. The maximum velocity of the tidal-flood current at Greenock is only about half a mile per hour, as against 7 at the Mersey. There is no tidal bore at the Clyde, and a very rapid one at the Mersey. There is neither a bar nor any heavy breaking waves at the Clyde, but there are both at the Mersey. There is only one cubic inch to one cubic yard of material in suspension at the Clyde, and 33 times as much at the Mersey. There is a depth of 20 fathoms at low water where the Clyde joins the sea; while there are only 9 feet at low-water at the bar at the Mersey, which is in the open and stormy Irish Channel.

In short, no two sandy rivers can well be more different

in their main features than the Mersey and the Clyde. In the Clyde the tides are small and the currents languid; there is hardly any stuff in suspension; there is neither a bar nor heavy waves to shake up the stuff in shallow water. The only matter in suspension is sewage from the city of Glasgow, which, when deposited, is constantly removed by a large fleet of steam dredges, which remove from $1\frac{1}{4}$ to $1\frac{1}{2}$ million cubic yards from the channel every year. It will be seen, therefore, that if there be one river less likely than another to have heavy deposits of silt, the Clyde is certainly that river, and it cannot for a moment be compared, but should rather be contrasted, with the Mersey. Mr. Deas, the engineer for the Clyde Navigation Trustees, stated in evidence that there was no similarity between the Clyde and the Mersey.

*The Tyne.*—The rise of tide at the Tyne is 13 feet, while at the Mersey it is 30 feet. The velocity of the tidal current is $1\frac{3}{4}$ mile per hour at the Tyne, at the Mersey 7 miles per hour. There is no bore; and the bar has been deepened and sheltered by extensive breakwaters at present in progress, the depth being now increased over it from about 6 feet to about 20 feet; and though there are training walls, they have been erected so close to the land as to leave no receptacle for silt to be deposited; there is therefore hardly any similarity between the Tyne and the Mersey.

*The Tees.*—The last river referred to as being free from deposit though training walls have been adopted, is the Tees; but even though it had physically resembled the Mersey, in having features favourable to the formation of silt, which is not the case, the best means have been already employed by Mr. Fowler for counteracting the evils of silting, by the extension of the training walls nearly down to the sea, and by the practical annihilation of the bar, by the erection of directing

breakwaters, which have acted so successfully on the currents that there is now 17½ feet of water where there was formerly a bar with a depth of only 3 feet 4 inches, so that this source of the formation of silt may be said to have now been eradicated, while the sandy beaches on which the waves break have been all excluded from the channel. But, in point of fact, there are comparatively few of those natural features which favour the formation of silt in the Tees at all. For the tide rises only 15 feet, and the matter in suspension in the lower channel is less than 1 inch per cubic yard, and the tidal velocity is only 4½ miles an hour; so that no argument applicable to the Mersey can be derived from the Tees, any more than from the Tyne or the Clyde.

*Loss of Scouring Power at the Mersey.*—We have lastly to calculate the numerical results at the Mersey of applying the principles which have been laid down, and the data which have been adduced so as to meet the objection that while the training walls in the Nith, Lune, and Ribble have been followed by large deposits of silt, those rivers have, upon the whole, been greatly improved instead of having suffered damage. Now, we originally explained that while the existence of any of the five characteristics which favour deposit must unquestionably have done some evil in connection with the walls at the Nith, Lune, and Ribble, the amount of that evil must have been proportional to the relative widths of their land-locked estuaries. In the case of the Lune, for example, the part of the estuary which is now silted up to the grass level, and contains 5,536,960 cubic yards of solid material, had it been three miles wide, as at the Mersey, instead of being only one, would have by this time contained a vast deal more stuff, and so have displaced a far larger amount of

tidal water than has actually been the case. Assuming, then, as we have more than sufficient reason for doing, that as at the Lune, Nith, and Ribble, where deposit has taken place up to grass level after the walls were erected, deposit will also take place up to the same level in the Mersey, the total amount of deposit would in that river be about 460,000,000 cubic yards; and against this, on the other hand, the additional tidal capacity which will be gained by the improved Mersey channel will amount to only about 14,000,000 cubic yards, which, deducted from the above amount of accretion, still leaves a balance of 446,000,000 cubic yards of tidal scouring-water, which must ultimately be excluded from the sea by the estuarial works. In order to judge of the effect of this loss, we have next to contrast it with the total amount of tidal water above the level of low-water spring-tides, which at present enters the estuary from the sea at the mouth of the river at the Rock Lighthouse, and which fills the tidal basin up to Runcorn. This amount is about 733,000,000 cubic yards, and adding to it the average fresh-water discharges from the drainage of the Irwell and Mersey district, which I compute at about 9,000,000 cubic yards in twelve hours, but which must be discharged in six hours, because it does not escape during flood tides, there will be in all a total of 742,000,000, so that there will be permanently excluded from the estuary more than *one half of the whole tidal scour*, which at present keeps open the sea approaches to Liverpool outside of the Rock Lighthouse.

Calculating in the same way for a neap-tide, we get nearly the same proportionate result. The present tidal scour at neaps amounts to 278,000,000 cubic yards, or, adding the fresh-water discharge, in all, 287,000,000; leaving the amount which will be excluded (less 3,478,000 cubic yards, gained

by excavating new channel) 157,397,000 cubic yards, or about *five-ninths of the whole.*[1]

*Loss of Scouring Power at the Lune.*—Calculations made on similar principles show that while deposit to the grass level will exclude from the Mersey one-half of the whole present scouring power of that estuary, at the Lune there has as yet at least been only *one-tenth* of its scouring power excluded from the sea; but, as I have already stated, if, with the same depth of deposit, the Lune estuary had been, as at the Mersey, three miles wide instead of only one mile, the proportionate loss of scouring power would of course have been enormously greater.

*Mr. Walker's Opinion as to abstraction of tidal water at the Tay.*—I regret that I have no means of ascertaining the proportionate loss of scouring power at either the Nith or the Ribble, but I wish now to refer to a question which arose as to the scouring power of the river Tay, which during the years 1833 to 1844 was improved according to designs of my late father, Mr. Robert Stevenson, so that an additional depth of 4 feet and a tidal acceleration of 50 minutes were got up to the quays at Perth. The works, including two short walls in the upper and narrower part of the river, where it is gravelly, consisted mainly of steam-dredging, and no training walls were ever proposed to be erected in the lower and wider part of the estuary, where there is sand and silt; but in the year 1845 certain riparian proprietors proposed to embank land in the lower estuary, and the authorities of the important harbour and docks of Dundee became alarmed for the safety of their interests, and applied to the Admiralty to send an engineer of eminence to report

[1] Those figures are taken from Captain Hills, marine surveyor of the port of Liverpool, and have been verified by myself.

on the whole subject. The engineer selected by the Admiralty was the late Mr. James Walker, the then permanent President of the Institution of Civil Engineers, and the then acknowledged head of the profession in all maritime matters. In an elaborate report he condemned the proposed works on the ground that they would exclude *one-twentieth of the scouring tidal power* of the Tay. It is of course a difficult question to decide what proportion of loss of scouring power may in any case be risked. We have here, however, the opinion of the first engineer of his day, and the one who carried out most of the later improvements of the river Clyde between Glasgow and Dumbarton. But even although he may be thought to have been too cautious in this Tay question, no one surely can doubt that so large a loss as *one-half* of the whole scouring power of the Mersey is altogether inadmissible.

*Foyle.*—The only other river to which I would refer is the Foyle in Ireland, where works, under Messrs. Stevenson's superintendence, have been in progress for the last thirty years. This river is remarkable from its passing, on its way to the sea, through Lough Foyle, a sheet of water 11 miles long and 4 miles wide, and where, from fear of deposit, training walls —for which Parliamentary powers had been obtained and which were intended to be erected in the Lough—were abandoned, and steam-dredging substituted for them, though at greater expense; and this was done simply on account of the risk of deposit in Lough Foyle, although that river has a rise of only 9 feet of tide, a flood velocity of under 2 miles per hour, and where there is no bar of any kind whatever, and no dock or important harbour between the works and the sea that might have been injuriously affected.

I wish in conclusion to guard myself from being supposed

to have ascertained accurately the true relative valuations in the rivers referred to, of such phenomena as tidal velocities, and, above all, of ratios of matter in mechanical suspension, as nothing can be more difficult than to compare the physical features of different estuaries in these respects. All I have done was to state these two valuations as I have been best able to ascertain them, but I readily admit that they are from their very nature no more than approximately correct, depending as they do upon the times at which they were taken, the state of the weather, and the local circumstances, which are seldom all strictly comparable.

Before leaving this subject I have only to say that the views I have expressed regarding accretion are entirely in accordance with those that have all along been held by Mr. Lyster, the eminent engineer of the Mersey Board, and that his alternative mode of forming the canal along the margin of the high water mark from Runcorn by Ellesmere Port would avoid the risk of accretion in the estuary by keeping entirely free of the estuary itself. There can be no doubt that Mr. Lyster's alternative scheme would be much cheaper than that originally proposed by the promoters.

There is still no conceivable reason, nor has any reason ever been suggested, for supposing that while the Ribble, the Lune, the Nith, and the Dee, have been silted up to the grass level, the Mersey, a river strictly similar in character, should be excepted from the rule which regulates deposits. Nor should it be forgotten that this process, so clearly preindicated by the presence of *all the known* conditions, would in the case of the Mersey be out of all proportion more dangerous to the navigation. In that river alone, in addition to a very high rise and a very swift current of tide, a bar, a bore, and a large amount of floating matter in the water, we find an

enormous area of estuary ready to be silted up, and a great port and great interests thus immediately threatened.

*Truth of the Principles advocated proved in the past history of the Mersey itself.*—The truth of the principles herein advocated have, I think, been demonstrated in the history of the changes that have already taken place in the case of the Mersey itself. Having been asked to report on the improvement of Ellesmere Port, on the Cheshire bank of the Mersey estuary, where the extensive network of canals, known as the Ellesmere Canal System, enters the Mersey estuary at its widest part, I found, from facts communicated by Mr. Jebb, C.E., the engineering adviser of the Canal Company, which facts were corroborated by the testimony of all the sailors and pilots I could find on the spot, that about 1872 the river Mersey had in the course of its meanderings or frettings gradually found its way across from the Lancashire over to the Cheshire side of the estuary. The effect of that great "fret" was not only to give Port Ellesmere one of the deepest channels it ever had, but the benefits of that great lateral excursion still, to some extent, exist on the Cheshire shore, though the depth has steadily decreased during the last nine or ten years, just in proportion as the river retraced its course back again to the Lancashire coast, where it now is.

Here, then, there is, as it seems to me, an absolute proof that the banks in the wide part of the estuary were kept down by the fretting, and are even still at a lower level than they would have been had the river never strayed across the estuary to the Cheshire side. If the river, even in its present state of nature, be prevented from making any similar excursions in the future from its present position, the rise in the level of the sandbanks which has already taken place, and is at the present moment going steadily on, must ultimately result in the

growth of grass; but if, instead of fixing the channel as it is, the present channel which is only about 3 feet deep were improved, as is proposed by being deepened to 12 feet below low-water level, and increased in breadth from about 300 feet to 600 or 800 feet, the grass-growing of the sandbanks would take place much more quickly, for such an improved channel having an enormously greater sectional capacity, would intercept and discharge in its present direction a far greater amount of tidal water, and wholly intercept all the great land floods that come down from the Mersey and Irwell drainage districts. All that water then, both fresh and tidal, would be confined within the present channel, and diverted for ever from the estuary behind the training walls. I hold then that the result of the great Ellesmere fret has shown, and still shows to the eye, that what was predicted as certain to take place if the channel proposed by the Bill of 1884 for the Manchester Canal had ever been made, has already *pro tanto* taken place in the history of the river. There need be no increased ratio of silting more than what has already occurred to produce the growth of grass, for without the construction of any new and improved channel, if the channel, small and shallow as it is, be but fixed in its present position, so as to prevent its ever straying again to the Cheshire shore, no higher ratio of silting than what has already taken place is necessary to produce the accretion of the whole estuary. All that is required, is simply to allow it to go on as it is doing at present, by fixing the present channel in its present position at the Lancashire shore, and the result is certain. It seems to me that there is no possible mode of explaining away this record of actual historical facts.

# CHAPTER XIII.

## MISCELLANEOUS SUBJECTS RELATING TO HARBOURS.

**Fishery Harbours—Mattress Breakwaters and Training Walls of Fascines—Groynes—Suspension Piers—Iron Piers—Piers connected with the Shore by an Open Viaduct—Floating Stages—Advantages of two Entrances—Danger of deepening entrances of Harbours of small Reductive Power—Movement of Heavy Shingle—Deposits—Shoaling of Inclosed Harbours—Cause of Inclosed Harbours keeping open—Artificial Scouring—Velocities of Currents—Scouring Power of Rivers—Dredging—Silt Pumps—Deposits in Docks—Checking Sand-drift—Commercial value of Harbours or Rivers increases as the cubes of the depths of water—Scend of the Waves—Height of Summer and Winter Waves—Mooring Pawls—Bollards—Fenders—Capstans—Loading and Discharging Coal—Steam and Hydraulic Cranes—Despatch of Vessels—Sir W. Armstrong's Hydraulic Apparatus—Timber Ponds—Tonnage of Ports—Harbour Lights—Advantages of Government supplementing Local Funds.**

*Fishery Harbours.*—During the last quarter of a century a very marked increase in the number, size, and equipment of the boats used in prosecuting the net and line fisheries on the eastern coasts of Great Britain has taken place, and, in consequence, there have been loud and repeated calls for extending, deepening, and improving fishery harbours. These harbours, unlike those for ordinary commercial purposes, do not require to be supplied with docks, steam cranes of large size, and the many other adjuncts which form the necessary accompaniments of harbours designed, as regards size, depth, and width of entrance, etc., for ships and steamers of the largest class, at

the quays of which cargoes of all kinds can be loaded or discharged. In short, fishery harbours and piers, though they do not exclude ordinary shipping, must be designed to meet the exigencies of a special kind of traffic as far as circumstances and funds permit, and require—

1. An entrance of not less than from 50 to 80 feet in width, and one which can be easily taken and left in different states of the weather; and also to have water deep enough to admit of boats of the largest draught taking it at low water springs, with a due allowance for the "scend" of the sea in addition.
2. Internal accommodation where the boats may lie in safety without necessitating the attention of the crew during the rise and fall of the tide, or during heavy weather. The area should be apportioned so as to accommodate from forty to fifty boats to an acre, according to the size of boats that frequent the harbour.
3. A due proportion between the internal area and the depth of water and exposure at the entrance. If this requisite be not kept fully in view in making the design, too much swell may be admitted into the harbour to allow the boats to lie in safety.
4. Quays of sufficient extent to accommodate the trade, protected by a parapet high enough to prevent spray or sea from passing over, so as to interfere with the discharging of the fish.
5. Where the harbour is much exposed provision should be made for allowing the waves to "spend" themselves on a sloping beach, and thus to prevent a recoil from upright walls.

6. A slip by which boats can be easily and expeditiously drawn out of the water and placed on dry land. These slips should be provided with hauling gear; and perhaps rails, laid in a manner somewhat similar to those of slipways, though not so heavy or costly, might with advantage be used, on which the cradle or truck could be made to travel more easily than over ordinary pitching.

7. Space for drying nets should be secured in the immediate neighbourhood of the harbour.

The great loss of life and property, especially on the East Coast of Scotland in the years 1848, 1857, and 1881, led to the discussion of the question whether it was better to improve existing harbours, or to provide, on a line of coast where the fishings are actively prosecuted, a "Boat Refuge Harbour," to which boats when overtaken by a sudden storm could run, with the certainty that they would, if able to reach it, lie in safety at all times of the tide and in all states of the weather. This question was remitted to Messrs. Stevenson, who, in the case of Banffshire, where the coast-line is practically straight, reported that one boat harbour of refuge would serve that coast, while in the case of Berwickshire, where the coast trends in different directions, forming two seaboards, more than one harbour of refuge would be required, and the conclusion that was arrived at was thus stated:—"We think that the obvious conclusion, from what we have said is, that it would be unwise, on the one hand, to restrict the expenditure of money to the formation of a single refuge harbour at one particular part of the coast; or, on the other, to restrict it to the deepening or other improvement of tidal harbours at many different parts of the coast. To put the matter suc-

cinctly, *both are best,* and we believe we are justified in saying that the wisest expenditure of money for saving lives and boats is to share it in some proportion between harbours of refuge and the erection and improvement of tidal harbours of the ordinary kind."

The boats now used in the fisheries are divided into three classes: (1) those of 30 feet keel and upwards; (2) those of 18 to 30 feet keel; and (3) those of 18 feet keel and under. Of the first class there are now engaged in the Scottish herring and line fishery 5382; of the second 4278; and ot the third 5724. As indicating the progress of the Scottish fisheries, it may be enough to state that thirty years ago the value of the boats of all classes was £225,830, while in 1884 it had reached £902,197, being nearly a fourfold increase in thirty years. This large increase in value is not entirely due to an increase in the number of the boats, but rather to the increase in their size. The following table gives the sizes of the largest boats used in the Scottish fisheries, and at other places:—

| Place. | Length of Keel. | Breadth of Beam. | Depth of Hold. | Draught Light. | Draught Loaded. | Tons Burden. | Cost of Boat ready for sea, with Sails, etc. | Cost of Nets. | Cost of Lines. | Number of Crew. |
|---|---|---|---|---|---|---|---|---|---|---|
| | Feet. | Feet. | Feet. | Feet. | Feet. | Tons. | | | | |
| Eyemouth | 50 to 56 | 17 to 18 | 7 to 8 | 4 to 4½ | 7 to 8 | 40 to 50 | £340 to £370 | £160 | £60 | 7 |
| Burnmouth | 50 to 53 | 17 to 17½ | 7 to 7½ | 4 to 4½ | 7 to 7½ | 40 to 45 | 340 to 350 | 160 | 60 | 7 |
| Coldingham | 47 to 50 | 16½ to 17 | 6½ to 7 | 3¾ to 4 | 6¾ to 7 | 35 to 40 | 320 to 340 | 160 | 60 | 7 |
| Port Seton | 59 | 18 | 8 to 9 | 5 | 7½ | 40 | 360 | 300 | 30 | 7 |
| St. Monance | 58 | 17 to 18 | 8 | 5 | 7½ | 30 to 36 | 360 | 250 | 30 | 7 |
| Anstruther | 58 | 17 to 18 | 8 | 5 | 7½ | 30 to 36 | 360 | 250 | 30 | 7 |
| Pittenweem | 58 | 17 to 18 | 8 | 5 | 7½ | 30 to 36 | 360 | 250 | 30 | 7 |
| Dunbar | 48 | 16 to 17 | 7½ to 8 | 4½ | 6½ | 25 to 30 | 340 | 220 | 25 | 7 |
| Wick | 50 | 17 | 8 | 5 | 7 | 25 | 300 | 200 | 20 | 7 |
| Collieston | 42 to 48 | 16½ to 17 | 7 to 7½ | 2½ to 3½ | 4 to 5 | 20 to 25 | 200 to 240 | 150 to 180 | 16 to 20 | 6 |
| Port Erroll | 45 to 48 | 16½ to 17 | 7 to 7½ | 2½ to 3½ | 4 to 5 | 22 to 25 | 200 to 240 | 150 to 180 | 18 to 20 | 6 |
| Boddam | 44 to 50 | 16½ to 17 | 7 to 7½ | 2½ to 4 | 4 to 5 | 20 to 26 | 200 to 250 | 150 to 180 | 18 to 20 | 6 |
| Peterhead | 54 to 56 | 17½ to 18½ | 7 to 8 | 2½ to 4 | 4 to 6½ | 20 to 30 | 230 to 340 | 150 to 300 | 20 to 24 | 6 & 7 |
| Buchanhaven | 45 to 51 | 16½ to 17½ | 7 to 7½ | 2½ to 4 | 4 to 5 | 20 to 25 | 220 to 300 | 150 to 190 | 20 to 24 | 6 & 7 |
| Fraserburgh | 58 | 18½ | 9′ 9″ | 3′ 10″ | 8 | 55 | 400 | 144 | 56 | 7 |
| Rosehearty | 59 | 18 | 9′ 4″ | 4 | 7½ | 60 | 400 | 144 | 56 | 7 |
| Montrose District | 45 to 58½ | 16′9″ to 17′2″ | 6′10″ to 8′9″ | 4 to 5½ | 8 to 9 | 20 to 37 | 280 to 340 | 180 to 210 | 36 to 56 | 6 & 7 |
| Stornoway | 54 | 17 | 9 | 3½ | 7 | 50 | 350 | 140 | ... | 7 |
| Great Yarmouth— | | | | | | | | | | |
| Herring Boat | 62 | 18½ | 9 | 6′ 3″ | 9 | 80 | 1200 | 450 | ... | 11 |
| Trawl Boat | 71′ 9″ | 19′ 5″ | 10′ 1″ | 7 | 10 | 120 | 1500 | Trawl gear, £60 | ... | 6 |
| St. Ives | 52 to 53 | 15′ 4″ | 7′ 6″ | 6 | 7 | 22 | 460 | £180 | ... | 7 |
| Lowestoft | 86 | 19 | 9 | 6 | 10 | 90 | 1200 | ... | ... | ... |
| Brixham | 60 | 18 | 9′ 6″ | 11 | ... | ... | 950 | ... | ... | 5 |
| Grimsby | 72 | 22½ | 10′ 6″ | 7 | 13 | 120 | 1900 including lines. | ... | ... | 11 |
| Isle of Man | 48 | 16½ | 8½ | 8½ | 9½ to 10 | 45 to 50 | 460 | 100 to 200 | ... | 8 |
| Kinsale | 49 | 14½ | 9 | 7 | 9 | 50 | 400 | 200 | ... | 8 |
| Fleetwood | 48 | 16 | 8 | 5 | 9 | 60 | 1000 with nets, etc. | ... | ... | 5 |

From the above table it will be seen that the length of the first-class boats in Scotland varies from 42 to 59 feet, and their draught when loaded varies from 4 to 9 feet, and most of them are either half or whole decked, which adds greatly to the comfort of the men, who are now enabled to prosecute the fishings at banks lying at distances of from 50 to 100 miles from the shore. This increase in size has, however, led to other difficulties—the boats cannot easily be hauled out of the water as was formerly the case. They are longer in being able to leave tidal harbours, and must either return sooner from the fishing-grounds, before the water has ebbed too far, or wait until the tide has risen sufficiently to enable them to get into shelter. Boats of the dimensions given above were almost unknown a quarter of a century ago, and they require havens of safety of an entirely different kind from those which were constructed for the accommodation of boats which were only from 28 to 35 feet keel. Indeed, the limit in the size of the boats must obviously be restricted by the depth and area of the harbours on the coast. Harbours with entrances deep enough to be taken by boats at all states of the tide are not numerous on the coast of Britain, and cannot be provided unless the local contributions are supplemented by aid from Government, or by loans at a low rate of interest, repayable by instalments. The near prospect of a large application of steam power to fishing craft should also be regarded as an element that must be taken into account in designing harbours for fishing purposes. Plate XXII. gives an example of a tidal fishing harbour.

The boats used on the West Coast of Donegal are small, being only about 24 feet keel and 3 tons burden, and, as a consequence, the fishermen are only able to prosecute the inshore fishings. To provide for this small craft, Mr.

Manning, engineer of the Irish Board of Works, has designed ports of a peculiar kind, and of a specially economic class, which would be quite unsuitable for the Scottish boats. Plate XXIII. shows one of the Donegal piers, from which it will be noticed that they consist of two main elements, viz. a low breakwater, under lee of which there is a boat slip. When the boats return from the fishing and have been discharged, they are immediately drawn up the slip wholly out of the water, and placed on dry land till they have again to go to sea.

*Mattress Breakwaters and Training Walls constructed of Fascines.*—There are in many parts of the world bays and arms of the sea of so shoal a character as to cause the waves to break several miles off the shore, but where difficulties of another kind arise from the soft nature of the subsoil; so that although there is no very violent sea to be encountered, yet breakwaters of concrete or masonry are unsuitable, owing to the softness of the bottom; for the waves, reduced though they be, are still able to produce sufficient reaction from the outer face of the breakwaters to plough up the bottom. In order to meet these difficulties structures called mattresses, which possess peculiar characteristics, have been resorted to in various parts of the world, particularly in Holland and America, where they have been found very suitable. In the well-known case of the river Mississippi, for example, Mr. Eads most successfully removed the bar by means of mattresses. The requisites for such structures are that they should be of small specific gravity and of open texture. They must also project but little above the bottom, so as to avoid coming within the direct influence of the breaking action of the waves, and thus to cause reaction, which would endanger the foundations. They must, in short, operate

strictly as submarine breakwaters in stopping the action of the waves at the bottom, while they also possess a certain amount of pliancy to enable them to adapt themselves to considerable variations in the level of the bottom, so as to deflect the underwater currents.

The following is the description, by Mr. E. L. Corthell,[1] of the mattresses used for the jetties at the South Pass of the Mississippi:—"The jetties are constructed of willow mattresses 100 feet in length, 2 feet in thickness, with a width varying from 40 feet at the foundation to 20 or 25 feet on the top. The mattresses are built on inclined timber-slips at the water's edge of willows cut on the various swamps beside the river, and towed to the site of the works in barges. Strips of yellow pine, 2½ inches by 6 inches, are first laid down 5 feet apart at right angles to the timber ways, and joined up to lengths of 100 feet; thus nine lengths are required for a mattress 40 feet in width. Turned hickory pins are then driven and wedged into 1⅛-inch holes bored in these at spaces of 5 feet. The willows are first laid transverse to the strips for a depth of 6 inches, then longitudinally for the same depth, and two more layers in the same way at right angles to each other. Cross-binders are next cut of the width of the mattress, with holes bored in them to fit the pins; these being then driven on, pressed down by levers, and secured by wedges driven in the ends of the pins, the whole is ready for launching.

"When towed off the slip the mattress floats about 4 inches out of water; it is then taken to its place at the guide piles, and a layer of stone evenly distributed over it sinks it into place. The mattresses are thus successively piled on one another, the width being diminished from 40 feet at the

[1] *Min. of Proc. of C. E. Inst.*, vol. 55, p. 368.

bottom to 20 or 25 feet at the top, the whole of the batter being given to the side of the jetty facing the channel, as the back is found to silt up so rapidly that it may be made vertical without risk. The last mattress is pulled into place by a steam-piling engine, and the final layer of willows is built *in situ* and fastened down by cross-binders and pins driven into the binders of the last mattress. In order to hasten the confinement of the stream and to carry the work more rapidly seaward, the first mile of the east jetty and the first 3000 feet of the west jetty were constructed of sheet-piling on a foundation of mattresses, but this was subsequently finished off with permanent mattress work. Two rows, 12 feet apart, of 12 inches by 12 inches guide piles were driven at distances of 8 feet; 6 inches by 12 inches walings were bolted to the row on the channel side, and sheet-piling, 5 inches by 12 inches at the upper end, and 3 inches by 12 inches at the lower, was driven 15 feet into the ground and spiked to the walings. The last 600 or 700 feet of the jetties is being constructed with a greater width of base than the rest, and with a batter on the sea-face to enable them to resist the action of the waves."

*Groynes.*—Fascines are also useful in protecting the banks of rivers; but in the open sea continuous lines of piling and planking, with occasional jetties, have been successfully employed at places where the coast was assailed by heavy waves. No general rule, however, can be laid down for coast-defence works, as much depends on the value of the property to be protected and the kind of materials which the district affords.

Mr. A. Dowson has suggested groynes for the protection of foreshores, the leading feature of which is that they are of open construction, so that the shingle is trapped, without

impeding the free passage of the waves. In this system the groynes consist of a series of iron gratings attached to uprights firmly fixed in the beach, the gratings being arranged so that when shingle has accumulated round them they can be raised when it is desired to cause a further deposit on a higher level. These groynes can be erected very quickly, and their first cost is less than that of solid groynes, and the repairs are trifling. They have been, Mr. Dowson informs me, in practical and satisfactory operation on the foreshore of St. Anne's, near Blackpool, for between two and three years, where, at spring tides, the sea wall is exposed to the full force of the waves from the Irish sea. The corporation of Brighton has also erected some of these groynes to protect a portion of their foreshore from the sea. Since their erection they have successfully withstood some of the most severe storms; and while the foreshore to the east and west of these groynes was lowered, the portion under their influence was not reduced.

*Suspension Piers.*—The suspension principle, which has been found so economical in spanning valleys where the undertaking would otherwise have proved impracticable, has also been occasionally resorted to in marine architecture. Where the beach is long and shallow a pier-head of timber or masonry, erected at or near low-water mark, can be easily and cheaply connected with the shore by means of a suspension bridge. The inducements to adopt the suspension principle are its economy and the free passage it affords to the currents, which in this way are prevented from forming accumulations of sand, silt, or gravel. The late Sir Samuel Brown erected two chain piers, the one at Brighton and the other at Newhaven, near Edinburgh, both of which are still in existence.

*Iron Piers.*—Piers of cast and of malleable iron are now frequently employed. Examples of these may be seen at Scarborough, Southport, Portobello, and at many other parts of the coast, and have been found to answer even where there is a considerable sea. At Scarborough pier I measured waves about 6 feet high, which struck upon the end of the pier without doing any damage.

The pier at Southport, described[1] by Mr. H. Hooper, is of cast iron, and the mode of sinking the piles was peculiar. "The piles proper, or lowest lengths of the columns, are cast in lengths of 8 feet and 10 feet, and are sunk into the sand to the depth of 7 feet and 9 feet respectively. They were provided with circular discs 1 foot 6 inches in diameter, to form a bearing surface, and a small hole being left in the centre, a wrought-iron tube, 2 inches in diameter, was passed down the inside of the pile and forced about four inches into the sand, a connection being made by means of a flexible hose between the top of the tube and a temporary pipe connected with the Water Company's mains, and extended as the sinking of the piles proceeded. A pressure of water of about 50 lbs. per inch was thus obtained, and this was found to be sufficient to force the sand from under the disc. Each disc was provided on the lower side with cutters, which, on an alternating motion being given to the pile, loosened the sand. The piles were gradually lowered, and guided by a small ordinary piling engine. When the pressure of water had been removed about 5 minutes, the piles settled down to so firm a bearing that, when tested with a load of 12 tons each, no signs of settlement could be perceived."[2] The cast-iron columns are 7 inches in external and $5\frac{3}{4}$ inches in internal diameter. All the piles, to the number of 237, were sunk

[1] *Min. Inst. Civ. Eng.*, vol. xx. [2] *Ibid.*, p. 293.

in six weeks, being at the rate of between 6 and 7 in twenty-four hours.

The Clevedon pier is of malleable iron. Mr. J. W. Grover[1] states that each upright consists of two Barlow rails weighing 80 lbs. to the yard, riveted back to back, and having a total section for each 100 feet span of 64 inches. They are braced together by diagonal tie-rods from $1\frac{3}{4}$ to $2\frac{1}{8}$ inch in diameter. The lower portions of the piles below low water are of solid wrought-iron, 5 inches in diameter, shod with cast-iron screws 2 feet in diameter, and were screwed down till a $4\frac{1}{2}$-inch rope passed round 6-feet capstan bars parted with the strain. They penetrated the ground to depths varying from 7 to 17 feet, and though made with a thread of 5 inches in pitch, seldom descended more than $2\frac{1}{2}$ inches or 3 inches in a turn. The solid pile-stems are connected with the Barlow rail piles by cast-iron shoes. Where rock occurred holes were jumped, and a 4-inch wrought-iron bar was inserted and secured by a jagged key. A shoe to receive the Barlow rail was fitted and keyed on this, and the remaining space was caulked with iron cement. The length of the longest pile is 76 feet. The level of roadway is 16 feet above extreme high water, and the height above the ground at the pier-head is about 68 feet.

*Piers connected with the Shore by an Open Viaduct.*—With the view of not interfering with the littoral drift of sand on the French coast, and at the same time providing a deep-water pier, at which vessels could call, at all states of the tide, the late Mr. Scott Russell and M. Dupuy de Lome[2] proposed to construct a sheltered landing-place at a distance of about three-quarters of a mile from the shore, near Calais. This deep-water landing place, which was intended to be in the

[1] *Min. Civ. Eng.*, vol. xxxii. [2] *Min. Proc. Inst. Civ. Eng.*, vol. lxx.

form of an annular island or circular wall, about 1000 feet in diameter, was to be connected by a bridge with the shore. The sheltered space was to be provided with quays so arranged as to allow trains, which were to be conveyed by large steamers across the Strait, being landed at any time of tide and conveyed across the bridge. This scheme, which was viewed favourably by the French Government, was stopped by the Franco-German War, and has not been revived.

Mr. A. M. Rendel designed a pier on the same principle for Rosslare, Ireland. This pier, which was intended for packet service and not as a regular commercial harbour, including a causeway or approach at the land end, a viaduct leading to a piled platform, and terminating in a solid breakwater, is about 1300 feet in length. The open viaduct is formed of iron girders resting upon concrete piers. The outer breakwater has not, however, been finished.

A work of a similar character is now being carried out at Port Elizabeth, South Africa, where it has been found that there is no movement of the sand from the beach farther seaward than in a depth of 3½ fathoms. It is proposed to carry a viaduct across the shallow water into a depth of 6 fathoms, and there to begin the solid work, which is to be 3000 feet in length, where shelter will be provided for ships discharging cargoes.

*Landing-Platforms or Floating Stages.*—A landing-platform or floating stage was first used, so far as I am aware, in the Mersey by Sir W. Cubitt. Recently, however, the floating stages at Birkenhead and Liverpool have been greatly extended by Mr. Lyster, the engineer of the Mersey Dock Board, and there are now three of them on the Mersey, one at Liverpool and two at Birkenhead, moored in the stream at

a distance of about 100 feet from the river-wall, and connected with the shore by heavy girder bridges, hinged to the river-wall and stage, and further secured by means of chain cables attached to heavy iron bollards. The Liverpool stage is 2063 feet long by 80 feet in width, and there are seven bridges giving access from the land, as well as a floating roadway constructed in sections, with hinged joints, by means of which an easy incline for carriage traffic is maintained at all times of tide. At Birkenhead there are two stages, the one at Woodside being 800 feet by 80 feet, provided with two bridges and a floating roadway similar to that at Liverpool. At Wallasey the stage is 352 feet by 72 feet, connected with the shore by two bridges. All of these stages are supported on iron pontoons, those at Liverpool being 80 feet by 10 feet wide, and 7 to 8 feet deep, while those at Wallasey are 70 feet long, 10 feet wide, and 5 feet deep. The depth of water at these stages varies from 12 to 30 feet at low water, and from 39 to 57 feet at high water of ordinary spring tides. Stages of somewhat similar construction have been erected at the Thames, at Bristol, and at other places.

*Advantages of two entrances to a Harbour.*—In every situation where it is easily practicable to make two entrances to a harbour it will be found well worth the additional expense, provided they can be so placed that the one shall be available when the other has become difficult of access. In harbours which have but one mouth, vessels are often detained for a length of time when the wind blows in such a direction as to throw a heavy sea into the entrance; at the Tyne, for example, before the river was improved, vessels drawing between 17 and 18 feet of water have been detained from two to three months after they were loaded, on account of a succession

of east winds on the days of high spring tides; whereas, if there are two mouths situated as we have supposed, vessels are at once enabled to take their departure from the sheltered side. At the port of Peterhead, the north and south harbours were, more than thirty years ago, united by a canal, and there the advantage has been of the most marked description. Vessels can now clear out as soon as loaded, either by the north or south mouth, according to the state of the sea. Some caution is necessary, however, in forming these communications, as where there is a high range of tide there is apt to be a strong current from one basin to the other.

*Danger of deepening the entrances of Harbours of small Reductive Power.*—One cause of disturbance in harbours, which is often not sufficiently considered, is the deepening of the entrance without making at the same time a proportionate enlargement of the internal area, or providing other works for counteracting the effect. As the depth of the water is increased waves of greater height reach the entrance, and thus gain admission to the interior. The truth of the principle that the *run* in a harbour increases with the depth of the entrance may be verified every tide at any exposed harbour, where it will be found that just as the tide rises the difficulty of keeping vessels at their moorings increases. At the port of Sunderland Mr. D. Stevenson recommended the removal of nearly the whole of the inner stone pier, and the substitution of works of open framework, in order to tranquillise the interior. These works, which have been quite successful, were rendered necessary by the frequent dredging and widening of the channel at and landwards of the entrance. Similar results have been experienced at other harbours. The following table shows some of the particulars of harbours which have suffered from disturbance by deepening :—

| | Area in acres and decimals. | Width of entrance in feet and inches. | Rise of tide in feet and inches. | Low-water depths at entrance. | | Amount of deepening in feet. |
|---|---|---|---|---|---|---|
| | | | | Former depth in feet. | Present depth in feet. | |
| Lybster (old harbour) . . . | 2·21 | 80 0 | 10 6 | 2 | 4 | 2 |
| Dunbar . . . | 4·01 | 58 0 | 17 0 | 0 | 4 | 4 |
| Sunderland (channel widened) . | ... | 320 0 | 14 6 | 3 | 4 | 1 |

*Movement of heavy Shingle by the Surf.*—Wherever the heaviest waves strike obliquely on the shore, the shingle, if there be any, travels across the beach, and is very apt to fill up the entrances to harbours. Examples of this may be seen in the English Channel and on the southern coasts of the Moray Firth. The kind of shingle that is moved to leeward will of course depend on the force of the surf.

*Deposits* are of two kinds (1) those lighter matters which are held in mechanical suspension in the water, and are gradually dropped as the water approaches to the state of stagnation; (2) those grosser and heavier matters, as well as lighter, which are rolled along the bottom or carried forward by the action of the waves and currents. The first-named deposits are found under *lee* of a pier or jetty which obstructs the waves or currents, while the second accumulate on its *weather* side, or at the entrance of a harbour. The second are generally due to the oblique action of the waves on the foreshore, while the first are irrespective of the waves.

One of the most remarkable cases of silting is that of the north channel of the Avon at the Bristol Channel. The silting began in 1865, when there was a depth of from 6 to 10 feet at low-water springs; up to 1867 it had not made much progress, but about the latter date the silting-up

became extremely rapid. The following is a list of the measurements taken during the year when the rate of silting-up was most rapid, as given by Mr. Mackenzie:—[1]

| | Depth. | | Depth silted up. | |
|---|---|---|---|---|
| | Feet. | Inches. | Feet. | Inches. |
| February 1868 . . | 24 | 3 | | |
| March ,, . . | 22 | 9 | 1 | 6 |
| April ,, . . | 20 | 8 | 2 | 1 |
| May ,, . . | 18 | 9 | 1 | 11 |
| June ,, . . | 16 | 8 | 2 | 1 |
| July ,, . . | 14 | 10 | 1 | 10 |
| August ,, . . | 13 | 4 | 1 | 6 |
| September ,, . . | 12 | 7 | 0 | 9 |
| October ,, . . | 11 | 3 | 1 | 4 |
| November ,, . . | 10 | 10 | 0 | 5 |
| March 1869 . . . | 9 | 2 | 1 | 8 |
| | | | 15 | 1 |

"This shows," says Mr. Mackenzie, "an average rate of accumulation of mud during twelve months of 1′ 3″ per month. The total length of the channel silted up was about 1000 yards, and the total depth of water 41 feet. There is still (in 1878) a depth of about 6 feet of water in the channel at high water of spring tides, and the accumulation of mud during the last few years has been hardly appreciable."

*Shoaling of Inclosed Harbours.*—It is a mistake to suppose that, when water is inclosed by solid piers, there must necessarily be a great deposit. This misconception gives rise to the reports which are so frequently made, that basins constructed long ago have to a great extent silted up; and similar allegations are made, with as little foundation, regarding bays and natural creeks of the open sea. The only way to test the

[1] *Proc. Inst. C. E.*, vol. lv. p. 7.

truth of such statements is to procure accurate soundings and compare them with the original depths, when probably, in the great majority of instances, it will be found that there is no material difference from the oldest charts. These notions most likely arise from confounding *artificial* with *natural* channels. The shoaling of channels which have been dredged deeper than the original bottom forms no proper ground for predicting a similar reduction of the depths due to the natural *profile of conservancy* of the shore, which generally preserves its symmetry with remarkable persistency, even within artificial inclosing walls.

*Cause of Inclosed Harbours keeping open.*—Captain Calver, who is strongly opposed to close harbours, on the ground that they will fill up, makes an exception regarding small tidal harbours, which he says are kept clear by the "scavenging process" of high winds during ebbing tide, and that the "most diminutive lipper" is effective in moving the lighter kinds of deposit.

The surface-ripple described by Captain Calver will, no doubt, have a certain effect. But there must surely be some other cause greatly more powerful and efficient than this to keep open our ports and harbours. The "*run*," wherever there is a *ground-swell*, and even the ordinary waves produced by a gale, are, I think, the agents which possess all the powers that are required; for although the depth at the entrance be considerable, yet, when the wind is strong, the surface undulations become, partially at least, waves of translation. Each wave, as it enters the basin, will therefore import a certain quantity of water, which must ultimately escape seawards through the entrance, otherwise the water would stand higher within the harbour than in the sea outside. The under-surface current thus produced runs probably

very near the bottom. Hence the detritus and silt that would be left in the basin, were there no such current, is carried out again into the open sea. That the quantity of water so brought in cannot be very small may be judged of from the fact that, during a gale in the Irish Sea in 1842, I counted 9.6 waves per minute, so that about 14,000 waves broke on the shore during twenty-four hours. Although each wave injected but a small portion of its contents into a harbour, it is quite conceivable that that water, returning seaward, should prove efficient as a *scouring* power, or at least in preventing the entrance of silt near the bottom. Mr. J. Wilson of Sunderland expressed the opinion some years ago in the *Engineer's Magazine* that when there is an *on*-shore wind there must necessarily be an *off*-shore current, and Mr. Cleghorn of Wick also maintains similar views. There can be no doubt, I think, of the accuracy of these opinions; but, as stated above, a *ground-swell* will generate in a close harbour an outgoing current even in the calmest weather, and so limit the amount of remaining deposit.

*Artificial Scouring.*—The preservation of the depth of harbours at a level *lower* than that of the original bottom involves both uncertainty and expense. Where the deposit is confined to the space between high and low water marks, the scouring by means of salt or fresh water is comparatively easy; but where it forms a bar outside of the entrance, the possibility of maintaining permanently a greater depth becomes very doubtful. The efficacy of the scour, so long as it is not impeded by enlargements of the channel, may be kept up for great distances, but it soon comes to an end after it meets the sea. When the volume of water liberated is great compared with the *alveus* or channel through which it has to pass, the stagnant water which originally occupied the

channel does not, to the same extent, destroy the momentum, as where the scouring has to be produced by a sudden *finite* impulse. In the one case the scouring power depends, *cæteris paribus*, simply on the relation subsisting between the quantity liberated in a given space of time and the sectional area of the channel through which it has to pass; while in the other it depends on the propelling head, and the direction in which the water leaves the sluice. Mr. Rendel's scheme for Birkenhead was on the former principle, which, it must be recollected, is only applicable where the soil is easily stirred up.

*Effective Velocity of Scouring.*—The quantity proposed by Mr. Rendel for scouring at Birkenhead on average spring tides was 1,600,000 cubic yards, to be liberated in the short space of three-quarters of an hour.[1] In all cases of scouring, it is of course an essential condition that such a velocity be generated as is necessary for acting upon the soil. The largest amount of back-water will be inoperative if it has less than what may be called the *effective velocity*, or that required for acting on the material which forms the bottom. If, for example, the discharge of the waters of a river be equalised by the construction of regulating reservoirs, there will be an actual diminution of scouring power, because a *sudden* flood could remove what the same, or even a much greater quantity of water, would never effect if liberated more slowly.

The first example of artificial scouring in this country seems to be due to Smeaton, who used it effectively at Ramsgate in 1779. At Bute Docks, Cardiff, designed by the late Sir W. Cubitt, the access to the outer basin is kept open

[1] *Port and Docks of Birkenhead*, by T. Webster, M.A., F.R.S. London, 1848, p. 27.

most successfully by means of artificial scouring on a large scale. The entrance was cut through mud banks for a distance of about three-fourths of a mile seaward of high-water mark. The initial discharge when the reservoir is full is stated to be 2500 tons per minute. I have known even so limited a discharge as one ton per second produce very useful effects in keeping a small tidal harbour clear of sand.

*Duration of Scouring.*—Minard holds that when a channel has to be maintained by regular and habitual scouring, the whole effect is generally produced in the course of the *first quarter of an hour*. This was made the subject of particular investigation at Dunkirk, where sections of the channel were made before and during the scour; and it was found that there was no alteration in the sectional area after the first quarter of an hour.

*Reservoirs for Scouring.*—Minard points out, as the best *form for scouring reservoirs*, that which will admit of the largest discharge in a given time; or, in other words, where the mean distance from the orifice is a minimum. Such a form is obviously the semicircle having the point of discharge in the centre. He also adduces the following examples of artificial scouring. At Calais the first scour removed about 100,000 cubic metres of sand = 130,800 cubic yards. At Dieppe one scour removes about 1500 cubic metres of sand = 1962 cubic yards. At Ostend, about 500 cubic metres = 654 cubic yards; and at Treport, according to Cessart, 3000 cubic metres of gravel = 3924 cubic yards, were removed. When gravel is to be displaced it is very important that the discharge should take place a little before low water, but with mud and silt the longer the discharge continues the better, as it prevents the lighter matters from being brought in again.[1]

[1] *Minard*, p. 100.

At Sunderland Mr. Murray designed a reservoir of 34 acres, 4½ feet deep, which is discharged in quarter of an hour by means of eight sluices of an aggregate area of 495 superficial feet, which, less 10 per cent for friction, gives 444,312 cubic feet per minute, producing a velocity of 4·0911 miles per hour, and 3·166 along the bottom. The sluices are placed at different levels, so as to act on the whole mass of water at once, and the current is visible at a distance of 2000 feet from the point of discharge.

*Effective Velocities of Currents.*—For the velocity required to remove stones or shingle, Sir John Leslie gives the following formula :—

Where $a$ denotes in feet the side of a cubic block of stone or diameter of a boulder, and $v$ = the velocity of the water in miles per hour, which is capable of moving it along the bottom,

$$v = 4\sqrt{a}.$$

The annexed are the results of experiments made by various observers on the size of particles which are moved by currents of different velocities :—

| | | | |
|---|---|---|---|
| 3 in. per sec. | = 0·170 | mile per hour | will just begin to work on fine clay. |
| 6 in. ,, | = 0·341 | do. | will lift fine sand. |
| 8 in. ,, | = 0·4545 | do. | will lift sand as coarse as lintseed. |
| 12 in. ,, | = 0·6819 | do. | will sweep along fine gravel. |
| 2 feet ,, | = 1·3638 | do. | will roll along rounded pebbles 1 inch in diameter. |
| 3 feet ,, | = 2·045 | do. | will sweep along slippery angular stones of the size of an egg. |
| 6·56 ft. ,, | = 4·472 | do. | required at Havre and Fécamp to scour gravel.[1] |

The most recent experiments are by the late Mr. T.

[1] *Minard*, p. 106.

Login, of which a description will be found in the *Proceedings of the Roy. Soc. of Edin.*, vol. iii. p. 475. In these experiments, the results of which are appended, the stream seldom exceeded half an inch in depth.

| Nature of Materials. | Rate of rushing-in water. | Velocity of Current. | |
|---|---|---|---|
| | Feet per minute. | Feet per minute. | Mile per hour. |
| Brick-clay when mixed with water, and allowed to settle for half an hour | ·566 | 15 | ·170 |
| Fresh-water sand | 10 | 40 | ·444 |
| Sea sand | 11·707 | 66·22 | ·752 |
| Rounded pebbles about the size of peas | 60 | 120 | 1·37 |
| Vegetable soil | ... | 50 | ·56 |

Brick-clay in its natural state was not moved by a current of 128 feet per minute, or 1·45 mile per hour. It must be observed, however, that chamber experiments, such as those, cannot with any confidence be applied to the materials which form the bottom of extensive estuaries, where there are vegetable productions which bind the materials sometimes very firmly together, or where there may be a natural coherence of the particles, which destroys the facility of movement, which characterises the carefully-washed materials used in chamber experiments, conducted in a small box, subjected to the action of a small current of water.

*Scouring Power of Rivers.*—A most important matter, in connection with the improvement of rivers, is the ratio between the efficacy of a stream of water to remove solid matters and the velocity of its current. Formerly this was generally supposed to vary as the square of the velocity; but recently Mr. Wilfrid Airy[1] has asserted, and seemingly with good reason, that this should be as the sixth power, and

[1] *Min. Pro. Inst. of C.E.*, vol. lxxxii.

both he and Mr. Law have given formulæ based on this assumption. Mr. Law considers this law as applicable to detritus, which consists of loose and non-cohesive materials, but not to a bottom consisting of clay or such-like cohesive materials. Further experiments seem still to be wanted, before we can feel perfect confidence in the results of any calculation. Mr. Law assumes that the efficacy of the scour in a shallow stream is much less than in one of greater depth running with the same velocity.

*Dredging.*—Steam and hand dredgers are in frequent use both for the formation and preservation of harbours, and the former, in combination with other works, has produced the most important changes in our British rivers, converting some of them from insignificant streams to highways for the largest class of ships afloat. At the Clyde, Tyne, Thames, Tay, Ribble, and many other rivers, enormous quantities of material have been dredged without interfering with the ordinary traffic—the total quantity of stuff taken from the bed of the river Tyne between the years 1860 and 1882, for example, amounted to 66,000,000 tons.

Dredging by steam-power, unless under peculiar circumstances, when the "bag and spoon" or the bucket dredge between two lighters is employed, is all but universal, especially in large operations, as all kinds of material except fixed rock, including large boulders, can now be dredged with ease. The construction of powerful dredging machines is now carried on by many engineering firms, especially on the Clyde. The following are the particulars of one of the largest dredgers yet constructed. It was made by Messrs. Simons for the Clyde Lighthouses Trustees, to whom the conservation of the estuary of the Clyde below Port-Glasgow has been entrusted :—

| | | |
|---|---|---|
| Length between perpendiculars | 160 ft. | 0 in. |
| Breadth moulded | 30 ,, | 0 ,, |
| Depth moulded | 10 ,, | 0 ,, |
| Sheer of deck | 2 ,, | 0 ,, |
| Rise of deck | 0 ,, | 10 ,, |

The engines, which are compound surface condensing, are 350 I.-H.-P., cylinders 23 and 44 inches diameter, with a 30-inch stroke, and make 65 to 70 revolutions per minute. She can dredge 500 tons of mud, clay, free sand or gravel per hour, and can work in any depth from 6½ to 35 feet under water. She is fitted with propelling gear, and steams at 5 miles per hour. The buckets for ordinary material are 3 feet 4 inches by 3 feet 2 inches, and a set of smaller buckets, of about 7 cubic feet capacity, is also used for working in boulder-clay. The cost of this dredger ready for work was £19,600. The 3-screw hopper barges for serving this machine are of the following dimensions:—

| | |
|---|---|
| Length between perpendiculars | 153½ feet. |
| Breadth moulded | 26 ,, |
| Depth moulded | 13 ,, |
| Hopper—Length | 65 ,, |
| ,, Breadth at top | 20 ,, |
| ,, at bottom | 9 ,, |

Each barge is capable of carrying 500 tons of dredged material, and of steaming, when loaded, at the rate of 9 knots an hour. The engines are inverted cylinder compound surface condensing, and capable of working up to 220 I.-H.-P. The cylinders are 19 and 36 inches diameter, with a stroke of 24 inches. Each barge complete cost £7400.

*Hopper Dredges.*—Messrs. Simons and Company, Renfrew, have made twenty hopper dredges, which combine the ordinary dredge and a hopper barge in one. The material is dredged

in the ordinary way, and instead of being discharged into a barge lying alongside it falls from the buckets into the dredger itself, the same engines performing the double duty of working the buckets and propelling the ship to the place of discharge. These machines are very useful where the space is limited or much crowded with traffic. The following are the dimensions of the largest hopper dredge which has yet been constructed :—

| | |
|---|---|
| Length between perpendiculars . . . . | 209 feet. |
| Breadth moulded . . . . . . | 40 „ |
| Depth moulded . . . . . . . | 14½ „ |
| Sheer of deck . . . . . . . | 1 „ |

This machine is fitted with two independent sets of compound engines of 700 I.-H.-P., diameter of cylinders 22 and 38 inches, with a stroke of 2 feet 3 inches. She has two mild steel boilers, 13 feet diameter, 9½ feet long, constructed to the Board of Trade requirements, for a working pressure of 70 lbs. The buckets have a capacity of 11 cubic feet, and the hopper is capable of containing 1300 tons of dredgings. She can dredge in from 6 to 35 feet of water, and steam at the rate of 7½ knots when loaded, or 8½ knots when light, and her cost was £33,000.

*Priestman Dredge.*—Messrs. Priestman have introduced into this country a dredge, which consists of a barge on which is placed one or more steam derrick cranes. From the derrick a bucket or scoop of wrought-iron is suspended over the side of the barge, which is lowered with its jaws fully open, and when it has reached the material to be dredged, the jaws are made gradually to close, thus digging into the stuff and retaining it, the effect of heaving up being to close the mouth of the bucket. The buckets are made of a capacity varying from 5 to 40 cwts.; and their shapes are

also varied to suit the nature of the material to be dredged, the jaws terminating in powerful teeth for excavating compact clay. The small machines can dredge in from 3 to 25 feet, while the larger ones can dredge at much greater depths. The barges can, of course, be made with propelling gear like hopper dredges. These machines are now extensively used for keeping docks clear of silt, and by simply changing the form of the grabs they can also be used as excavators.

*Dredging in Exposed Situations.*—From special observations which I had made for me by Mr. M'Donald, resident engineer at Loch Foyle, when the dredge was at work, it appears that the dredging cannot proceed when the waves exceed or approach 2½ feet; and this is also the experience at the Clyde.

"When the waves rise to 2 feet or 2½ feet," says Mr. M'Donald, "we then let the vessel's head come to the wind and waves, when she rides much easier than when lying broadside. We find the punts are worse to handle than the dredge; they are so short that, with a 2½ feet wave, they would roll all the stuff off their deck in a short time; and if we took them near the dredge they would soon either destroy themselves or the machine, or probably both. It is also severe on the dredge to work when the seas are above 2½ to 3 feet high; the weight of the buckets and ladder on the stem, and the engine and coals on the bow, tends to strain the vessel amidships. It is but seldom we have a wave even 3 feet high."

Lough Foyle is about 11 miles long and 4 miles broad, and, as will be seen from the table on page 27, waves of 5 feet in height are sometimes generated during gales; yet the dredge with her punts, although unable to work, can ride in safety when exposed to waves of this height.

The late Mr. Ure told me he had never tried the large Tyne dredge in rough weather, but with other dredgers of the usual

size he has never "done any good with more than a *two-feet sea.*"

*The Removal of Silt by Pumping.*—The late Mr. Duncan, engineer of the Clyde Navigation, kindly sent me the following extract from M. Leferme's Report of 30th September 1859, on the result of M. Gache's silt-pump of 20 horse-power at St. Nazaire :—

"The experiment has now been made on a scale vast enough to warrant giving an opinion on its merits. A longer trial might suggest the necessity of making some slight modifications in the details, but we are bound to consider the aim as having been completely attained. The silt lifted by the pumps is not, as might be supposed, mixed with water. When fairly set agoing, the density of the silt lifted with the pumps is 1·19, being evidently the muddy layer in which the sucker is at work, and which is sunk in the mud for 40 or 50 centimetres (about 18 English inches). A phial filled with the mud drawn up with the pumps, after being hermetically sealed, and allowed to stand for thirty-six days, had only a film of water on the top of about ·005 in thickness.

"The time required for loading the boat (which contains in its wells 225 cubic metres), transporting and discharging, including the time lost in passing through the double lock-gates, is on the average 4½ hours. . . . The metre cube of mud lifted from the basin and carried 1500 metres has as yet, all expenses included (excepting interest of capital), amounted to 16 centimes (1¼d. per cubic yard)."

Mr Duncan informed me that he found this plan did not answer at the Clyde. Although the rose was buried several feet in the mud, nothing but discoloured water was ever lifted. The material was so porous[1] that the water percolated freely through it, and being the lighter body was lifted by the pump in a considerable stream.[2]

[1] Its specific gravity was 1·46, that at Nazaire 1·19.

[2] *Min. Civ. Eng.*

*Dredging by Injection and Suction.*—To keep open the entrance to Dunkirk Harbour a new kind of dredger has been successfully employed. The dredger, which is of iron, has a hopper capacity of 185 cubic yards of material; and when loaded draws 9 feet 10 inches, and steams at 7 knots. The engine is 150 horse-power, and works either the screw or suction pumps.

"The dredging is effected by the twofold action of streams of water injected under pressure into the sand, and by exhaustion; for each of which operations a separate centrifugal pump is used. One pump draws water into an air chamber, and thence to a hydraulic injector or sand-pump. The lower end of the injector, which rests on the bottom, is made of cast-iron, so as to sink readily into the sand. The water injected under pressure down one pipe passes out of three small tubes projecting slightly from the casting and stirs up the sand, which is then, together with the water, drawn up a separate pipe by the action of the other centrifugal pump. Both these pipes are made flexible at their extremities, so that the contact of their lower ends with the bottom is in no way affected by any rolling or pitching of the vessel."[1]

The dredger is capable of working in a 2 feet swell, and can raise from 52 to 78 cubic yards per hour, according to the state of the sea.

*Deposit in Docks.*—It is probable that in some *docks* the deposit may be of a density that would admit of its being pumped. The annexed table of deposits for different ports is from *Minard*:—

TABLE of Deposits in Docks (*Minard*).[2]

| | Inch per day. |
|---|---|
| Ramsgate | ·157 |
| Hull | ·118 |
| Flessingen | ·197 |
| Havre | ·276 |
| Honfleur | ·787 |

[1] *Proc. Inst. C.E.*, vol. 56. [2] *Minard*, p. 95.

MEDITERRANEAN PORTS.

| | Inches per annum. |
|---|---|
| Marseilles | 0·236 |
| Cassin | 3·937 |
| Ciotat | 1·456 |
| Bouc | 0·394 |

At the old dock of Grimsby fresh water is supplied by land streams, from which, unlike the water of the Humber, there is little deposit. At Cardiff, instead of using the Bristol Channel, which has much silt in mechanical suspension, the waters of the river Taff are used for supplying the Bute docks, while the docks at Penarth are entirely supplied by the tide water of the Bristol Channel.

*Checking Sand-Drifts.*—Though the sea, with its restless waves and ever-varying tides, will always demand the greatest share of the engineer's vigilance and attention, yet it is not the only foe with which he has to contend. There are difficulties to be met on the land as well as on the sea. When high winds sweep across a large tract of barren sand, large quantities may be deposited in docks or harbours. At Ostend the sand, even when wet, has been carried by the wind to very considerable distances.

Different devices have been tried for checking sand-floods. High stone walls have never, in any instance that I have known, been found to do much good. At the harbour of Nairn a slight fence about 8 feet high, and consisting of spars of wood from 3 to 5 inches broad, and fixed from 1½ to 3 inches apart, has been found more efficient than an altogether impervious barrier. At Mullaghmore Harbour, in the county Sligo, Lord Palmerston planted a species of pine tree for checking the incursions of sand, on the advice of the late Mr. R. Stevenson, who had been struck with the vigorous growth of the *Pinus maritima major* on the shores of the Bay of

Biscay. In his report to Lord Palmerston in 1839, Mr. Stevenson recommended that pine cones should be procured from France. A kind of bent grass was, on the suggestion of the late Mr. Lynch, Lord Palmerston's land-steward, planted on the side next the sea, so as to act as a protection to the pines during their first growth. The result of the experiment has been highly successful, having established the fact that the *Pinus maritima major* is, in certain circumstances, nearly as well adapted to our own coasts as to the coasts of Normandy, a fact which deserves to be more generally known.

The following information was communicated by Mr. Kincaid of Dublin, as to the present state of these plantations :—

"The Mullaghmore plantations extend to about 200 acres. About 80 of these were planted about forty years ago. The remainder were planted twenty years ago, and are making fair progress. All the pine plantations from opposite Newtown Cliffony to Mullaghmore are in a most healthy condition, the trees making growths of from 12 to 20 inches each year. The storms have no bad effect on the south side of the great sandhill, but on its summit, and towards the west side, the spray and gales of the Atlantic will not allow the young trees to make any progress."

A somewhat similar method was adopted, in 1850, of improving an immense territory of uninhabited, poor, sandy, unproductive soil, comprising an area of nearly 2,000,000 acres, and designated "Les Landes de Gascoyne." This desert territory extended from the mouth of the river Gironde along the shores of the Bay of Biscay for a distance of about 140 miles. The land resembled a vast and nearly horizontal plain, at an average altitude of about 330 feet above the level of the sea. Part of the ground was drained and sown with fir seeds and acorns, and in less than five years the trees had

grown to a height of nearly 12 feet, each tree being about 12 inches in circumference at the ground. This experiment being satisfactory, a general plan for draining and sowing the waste lands was prepared, and upwards of 1½ million of acres are now under forest cultivation, consisting mainly of fir trees. Some of the timber, which was in its twenty-eighth year of growth, sold at £17 : 9s. per acre. In seventy years the value of the timber will be about 50 millions of pounds sterling for the produce of lands which were recently a desert, and the district is now one of the healthiest in France.[1]

*Commercial Value of Harbours or Rivers increases as the Cubes of the Depths of Water.*—It is not wonderful that the risk of admitting more *run* into a harbour should often be disregarded in acquiring a greater depth; for the commercial advantages are not proportional simply to the additional depth, but they increase in a much higher ratio. Besides, there is a further advantage due to increase of depth. For example, Mr. George Robertson has shown that by making the Albert Dock at Leith 2 feet deeper than the Victoria basin, there are 296 tides in the year in which there will be a depth of 23 feet, whereas at the Victoria there are only 102 tides in the year in which that depth occurs. The river Tyne furnishes a good example of the advantages of additional depth. Previous to the year 1860 no vessel drawing more than 20 feet could enter or leave the river even at high water of spring tides, and whenever an east wind occurred the available depth was diminished according to the height of the sea waves. The bar, on which there was only 6 feet at low water, was deepened to 20 feet, and the result is, that whilst in 1854 the average tonnage of all vessels using the river was 149 tons, in 1873 it was 274 tons; in 1880,

[1] *Min. Pro. Inst. C.E.*, vol. lv.

359½ tons; and in 1882, 386 tons: and the number of vessels above 500 tons register, which was 422 in 1863, was 4453 in 1880 and 4827 in 1882, a considerable number being large vessels of over 2000 tons register—a size unknown in the river until after 1863.

From an examination of the proportions of a considerable number of vessels, it turns out that, although there seems to be not much uniformity in the ratio of tonnage to draught among steam-vessels, whether propelled by paddle or screw, yet there appears, on the average, to be a tolerable amount of uniformity among ordinary sailing vessels constructed of timber. I have found that, although even among sailing vessels there are marked peculiarities in the build, the following simple formula, deduced from a somewhat extended examination, gives a fair general approximation to the tonnage. It cannot, however, be regarded as more than *approximately* true. Where $d$ represents the draught in feet, $t$ the burden in tons, and $a$ a constant depending on build,

$$t = \frac{d^3}{a}, \text{ and } d = \sqrt[3]{at}.$$

The ratio of draughts to tonnage has been gradually decreasing, but for the general run of timber vessels built twenty to thirty years ago $a$ may be taken $= 10$; and for those at present frequenting our ports $a$ may perhaps be assumed as $= 9$ for vessels up to 500 tons, though very many of the larger class of vessels lately built would require a factor of only about 7½.

Assuming the smaller factor, we have the following formula, which will be found convenient for comparing numerically the commercial values of different depths for a harbour or navigation—

$$t = .13d^3, \text{ and } d = \sqrt[3]{7.5t}.$$

Where $t$ = maximum tonnage of ships capable of using the port, whether at high or low water, and $d$ = the depth of water in feet at high or low water, as may be required. Thus the capacity for trade of a channel 10 feet deep will be increased *eight times* if its depth be increased to 20 feet.

We are justified in inferring that *the capacities for tonnage of different channels vary as the cubes of their depth*—a law which may be found useful when comparing the relative advantages of two navigable tracks.

*Vertical Scend of the Waves.*—If the weather be perfectly calm, ships may enter a port, although their keels are almost scraping the bottom; but if there be any surge, the available depth becomes very considerably decreased by the vertical "scend" or plunge of the ship below the mean level of her keel.

*The ruling* or *available depth of a harbour* may be termed *the minimum navigable depth of water, reduced for "scend," which a vessel can depend upon finding at low water of ordinary springs throughout the track leading from the open sea to a safe berth within the harbour.*

"The 'scend' of vessels," says Mr. Meik, as estimated at Sunderland, "is the lift of the vessel, and is ascertained by taking the perpendicular space the vessel moves through, or the space between the position of the keel at its lowest to its position at its highest elevation. To arrive at what is the greatest draught at which a vessel can pass over the bar, we have generally deducted the 'scend' from the registered depth on the gauge, but properly only the space between the level of the keel of the vessel in smooth water and at its lowest level when passing through a wave should be deducted. This, I consider, would be too fine for practice. I

cannot tell whether our rule is adopted at other ports; it is, however, used here very generally. When passing over a wave with a 10 feet lift, some of our small colliers would scend 7½ to 8 feet, whereas a long screw collier of 180 feet in length would only scend 5 feet. We have ascertained this from actual observations. The scend is *generally* taken at *two-thirds* of the greatest lift of the wave for ordinary colliers, and *one-half* of the lift of the wave for large screw steamers—taking in both cases the lift or height of the wave to be from the lowest fall to the crest. We take principally by the eye, or in the proportions I have stated, if only the extreme height of the wave is returned. We have frequently checked this when vessels struck slightly, and we have found it to be very correct."

*Height of Summer and Winter Waves.*—The accompanying diagram (Fig. 32) of the height of the waves at Lybster

REGISTER of HEIGHT of WAVES for 1852, observed at Lybster, Caithness-shire.

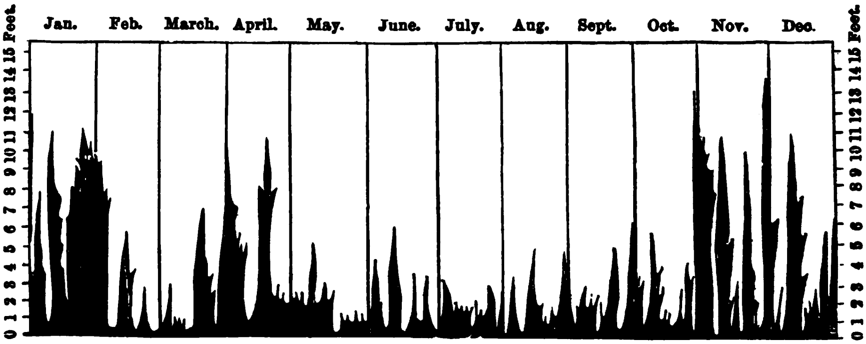



Fig. 32.

Harbour is given for the purpose of indicating graphically the suddenness with which our eastern coast is visited by

gales, and the comparative eligibility of the summer and winter months for carrying on marine works.

*Mooring-Pawls.*—Stone, cast-iron, and timber, are used for mooring-pawls. Fig. 33 represents a cast-iron pawl, and Fig. 34 is one formed of stone. The best materials for the latter are granite, limestone, or other tough material. Cast-iron pawls have been perforated on the top, so as to give an exit for compressed air at piers which are exposed to a heavy sea.

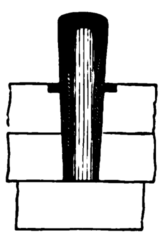


Fig. 33.

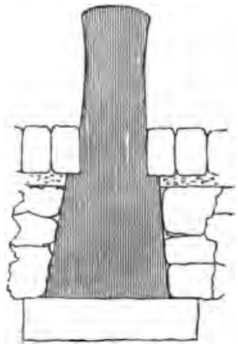


Fig. 34.

*Bollards.*—In addition to pawls and rings bollards of cast-iron are largely used for mooring vessels. They are built into the quay walls close to the front, thus preventing the quays from being encumbered with ropes.

*Fenders.*—For the mutual protection of ships and the quay-walls at which they lie, fenders of timber are fixed to the masonry at such distances apart as to suit the length of the vessels or boats that frequent the port. They prevent the grinding action of the vessels' sides against the masonry, while they distribute the pressure over a large surface, and thus prevent undue force from coming on any single stone.

*Capstans.*— Capstans, worked by handspokes or by hydraulic power, are common and useful adjuncts at the entrances to harbours. At the one which is placed in the port of Honfleur, near Havre, I noticed a simple expedient, which has been adopted for preventing ships' cables from *riding* when being coiled on the drum. It consists of an iron ring about 4 inches in width and about 2 inches thick, which encircles the capstan, and which is gradually pushed upwards as more and more of the cable is coiled on the drum. The heavy ring is thus constantly pressing upon the cable, so as to prevent it from rising too high on the barrel.

*Loading of Coal and Coal Staiths.*—It is of importance in discharging coal into ships that the fall should be as small as possible in order to prevent breakage. The height from which coal is loaded at different docks, according to the system employed, varies from 15 to 36 feet — the most common heights being from 20 to 27 feet. At Greenock, where steam cranes are used, they load about 500 tons a day. At Middlesbrough and at Penarth they can load 150 tons per hour, but 106 are as much as can be trimmed on board.

Mr. Messent says that at the wharf at the Northumberland Dock at the Tyne there are two shipping staiths which project into the river 97 feet from the quay, where there is a depth of 25 feet at low-water spring tides. These staiths are self-acting; the loaded waggons, brought within about 540 yards by locomotive engines, descend to the shipping spouts by their own gravity, and after discharging their loads, the empty waggons run off the staith to a siding at a lower level, from which the locomotives can take them. Each of the staiths has three spouts, so that coals may be simultaneously loaded into three hatchways of a ship; and the upper staith is constructed so as to commence loading, if necessary, at

high-water spring tides, a vessel of 20 feet side, or the hatchway coaming of which is 20 feet above the floating water line.

When the three spouts are used, from 800 to 1000 tons of coal per hour may be loaded into a vessel at each of the staiths.[1]

At Cardiff the loading of coal is done by tips—25 being balance and 17 hydraulic tips, and there is also a movable hydraulic crane capable of lifting 25 tons. The new tips have been made so as to have a range of lift of 27 feet. By the hydraulic crane a waggon of coals can be shipped in from 2½ to 3 minutes. Each tip, Mr. M'Connochie says, is capable of shipping 1000 tons per working day, the total shipping capacity of the port being nearly 12,000,000 tons of coal a year. In some instances as many as 200 tons have been shipped per hour at the hydraulic tips; and it is now not uncommon for a steam collier of 2000 tons burden to enter the basin at high water of one day, discharge her ballast, receive her cargo, and leave at high water the following day, the entire operation occupying less than twenty-four hours.[2]

*Discharging Coal.*—Coal-discharging cranes, worked by steam or hydraulic pressure, are either placed on the quays, or on floating stages, or on barges. The latter are so constructed as to admit of three cranes working over one ship, by which a vessel can be discharged at the rate of 200 tons per hour.[3]

*Ballast Cranes.*—At Swansea, with hydraulic machinery, they can discharge from 350 to 400 tons a day, and those at Penarth at the rate of 60 tons an hour.

*Cranes.*—All ports of any importance are now provided with either steam or hydraulic cranes, and some of these are capable of lifting very heavy weights. At Liverpool, for

[1] Parliamentary Return, *Harbour Authorities*, 1883.

[2] Paper read by Mr. M'Connochie at the Institution of Mechanical Engineers.

[3] *Min. Pro. Inst. C.E.*, vol. 50.

example, the cranes vary in power from 30 cwt. to 100 tons, and many other ports have cranes which lift up to 75 tons. The introduction of hydraulic power has added largely to the means of loading and discharging vessels at docks, as the movable hydraulic crane can be made to travel on a line of rails placed on the quays, so as to accommodate their positions to those of the vessels—they can be set instantly at work—and two or more cranes can be brought into operation to suit the different hatchways upon one ship. Hydrants, or points of junction with the pressure main, are placed at convenient distances along the quay, so that any crane can be easily connected with the nearest hydrant by means of telescopic pipes.

*Spezia Hydraulic Crane.*—Sir W. G. Armstrong[1] says—"The most notable example of this kind of hydraulic crane is that which has recently been erected in the Royal Italian Arsenal at Spezia, and which is capable of lifting 160 tons through a range of 40 feet. This crane is carried upon a ring of live rollers supported by a pedestal of masonry, and the slewing is effected by an hydraulic engine applied to a pinion which gears with a circular rack. The rake of the jib or projection from the centre of rotation is 65 feet, and its height from the quay-level is 105 feet. As the crane has occasionally to be used for comparatively light loads a chain is applied for that purpose, and is hauled up by a cupped drum worked by the slewing engine. The crane is counterbalanced on the side opposite to the load."

*Twenty-ton Portable Steam Crane.*—Messrs. Henderson Brothers, of the "Anchor Line" of steamers, had recently constructed for them by Messrs. Russell of Motherwell, for discharging their ships at Stobcross Wharf, Glasgow, a 20-ton

[1] *Min. Pro. Inst. C.E.*, vol. 50.

portable steam crane. Owing to the limited space between the edge of the quay and the sheds the gauge of the wheels is 10 feet centre to centre, and in order to clear the eaves of the shed the central post is only 2½ feet from the centre of the outside wheels. The outer wheels bear directly on the granite kerb, and the inner on a grooved rail. The carriage is of malleable iron plates, 1½ inch thick, 4 feet deep; the eight wheels on each side, being 3 feet centre to centre, give a wheel base of 21 feet. The central post is of malleable iron 2 feet diameter; the jib is 50 feet long, of malleable iron plates of box section, and its radius is variable by steam; the chain barrel is 2 feet 3 inches diameter, screw grooved for the chain, and there are double and single purchase gears. The engines have a pair of 9-inch cylinders by 13-inch stroke, with steel-link motion. The boiler is vertical, with three cross tubes, and a large cylindrical feed water tank is placed above it, through which the heat passes to the chimney; the exhaust steam is also led into it. The crane is moved along the quay by gearing fitted under the carriage, grasping by means of a cupped pulley a pitch chain made fast to any of the mooring blocks. The maximum working load is 20 tons at a radius of 30 feet, and 16 tons at 35 feet. Besides ordinary lifts, it is fitted with tipping gear for lifting coal waggons. The crane weighs 103 tons, and there is about 12 tons of iron ballast in the tank under the boiler, and 35 tons in the land side of the carriage, so that the total weight is 150 tons. The crane is found to work with extreme ease under the control of one man.

*Seventy-ton Cranes at Greenock and Glasgow.*—These cranes were made by Messrs. Taylor, Birkenhead. The crane at each port has a radius of 57 feet, and its total height is 71 feet. It was tested first with a load of 70 tons of pig-iron, which,

with a pressure of 40 lbs. of steam, was lifted at the rate of two and a half feet per minute. It made a complete revolution in five minutes. Afterwards the crane lifted a load of 91 tons, being one ton more than the guaranteed test load, and raised it about 12 inches. The lifting chains are of $1\frac{3}{4}$-inch iron, and have been tested to 78 tons, which, with four plies, would be equal to 312 tons. Both cheeks and jibs are of wrought iron. Besides the principal crane, an auxiliary is provided for 10 tons and under. The auxiliary power lifts 10 tons at the speed of 10 feet in height per minute.

The roller-path and the 60 rollers are made of a material consisting of cast-iron and steel, with a small proportion of hæmatite iron, being, it is believed, about 16 per cent stronger and considerably more durable than the best ordinary cast-iron. No cast-iron is subject either to tension or torsion in any part of the structure; the main frame, jib, etc., being, as already stated, of wrought iron. There are two steam engines, one for hoisting and one for turning, so that both operations can go on simultaneously. The hoisting engine has cylinders of 10 inches and 16 inches stroke, and those of the revolving engine are 8 inches and 12 inches stroke. They are supplied from one vertical boiler. The most important strains are as under:—

| | Tons. |
|---|---|
| Tension on centre pin, with test load, and allowing for effect of overhanging structural weights on jib, block, etc. | 349 |
| Tension on each holding-down bolt, do. | 58 : 16 |
| Compression on jib, do. | 327 |
| Tension on tension rods | 259 |
| Compression on front roller-path, supported by 10 rollers, allowing in like manner for effect of overhanging weights, but excluding the weight of the body of the crane | 460 |

*Methods of Economising Time in the Despatch of Vessels.*—Where commerce is prosecuted with the energy which is now so common in our own and other countries, the value of time becomes greatly enhanced, and whatever tends to shorten the length of voyages, and the time of loading and discharging vessels, is justly looked on as a public benefit. The labours of Maury, for example, who has so skilfully studied the general laws which regulate the direction of the winds and the currents of the ocean, and which have resulted in much economy of time, have been universally and gratefully acknowledged by the shipping interests. Since the publication of his wind and current charts the voyage from Washington to the Equator has been abridged by 10 days. That from California, which used to occupy 183 days, does not now extend beyond 135. The average time of a ship between England and Australia, which used to be 124 days for going and as many for returning, is now reduced to 97 for going and to 63 for returning. The actual saving in money which has resulted from Maury's charts was estimated in 1854 at 2,250,000 dollars for the shipping of the United States alone.[1]

When so much has been done to abridge the length of voyages, it becomes an object not less worthy of attainment that proper despatch should be secured in the discharge and loading of cargoes after the vessel comes into port. "Had we been out a week or ten days earlier," says a witness on the Birkenhead Dock Bill,[2] "we should have got a freight which other vessels obtained. And at particular seasons of the year it is still more important, because, when bound on long voyages, the loss of a week is of very great importance. At a critical season it involves the necessity of the vessel

[1] *Les Phenomenes de la Mer, par Elie Margollè:* Paris, p. 70.

[2] *Port and Docks of Birkenhead:* Lond. 1848, p. 35.

taking a longer route, a much longer distance and longer in time, perhaps a month, that would very often throw her into a contrary monsoon in returning."

*Sir W. Armstrong's Hydraulic Apparatus.*—The principle of applying hydraulic pressure for opening the gates, bridges, and sluices, the capstans for hauling vessels out and into dock, the discharging of ballast, the loading of coals, and the shipment and discharging of general cargoes, has now been successfully adopted at many harbours. Its use is, however, only warrantable where there is a great amount of traffic. At the Victoria Docks, where it is employed, Mr. Bidder[1] mentions that, on the 12th May 1858, 41 craft and 17 ships, or 11,711 tons, came in at one tide. In the month of April 1859 the number of

| | |
|---|---|
| Craft entering the harbours . . . | 1229 |
| „ leaving . . . . . . | 1288 |
| Ships entering . . . . . . | 250 |
| „ leaving . . . . . . | 258 |

or an aggregate of 2517 craft and 508 ships during the month. The gates, which are 80 feet span, are opened in less than 1½ minute. At Sunderland the *accumulators* are equivalent to a head of 600 feet, and the engine is of 30 horse-power. The gates (60 feet) are opened in about two minutes, and closed in about the same time, by one man at each gate. A wrought-iron bridge 16 feet wide, and including counterweight equal to nearly 200 tons, is raised vertically 18 inches and drawn back in about 2½ minutes.[2] At Swansea the accumulators are equivalent to an effective pressure of 750 lbs. per square inch, and there are three high-pressure engines of 80, 30, and 12 horse-power respectively. The time em-

[1] *Min. Inst. Civ. Eng.*, vol. xviii. p. 486.

[2] *Ibid.*, vol. xv. p. 442.

ployed in either opening or closing the gates is about *two minutes and a half*, which is the shortest period consistent with safety. The wrought-iron swing-bridge can be opened or shut in *one minute and a half.* The quantity of coal that can be shipped by each machine is about 1000 tons per day, and the effective quantity of water required for the port is 21,050 cubic feet per week.[1] The saving of time effected by this method is very decided; for at Liverpool, according to Mr. A. Giles, gates 70 feet wide required 20 minutes and six men to open them. At Peterhead there is a swing-bridge with double roadway, from designs of Messrs. Stevenson, which, though not on the hydraulic principle, is moved with great ease. Each half weights 91½ tons, including 13 tons of ballast, yet it can be opened with one hand. The time required to raise the strut frame and open the bridge, with one man on each side, is about 2½ minutes. The large new bridge at Leith, designed by Messrs. Rendal and Robertson, and worked by the Armstrong apparatus, is 120 feet span, length of girder 214 feet, weight moved 750 tons, and is opened in 1½ minute.

*Timber Ponds.*—At some harbours there exist large timber ponds; those at the Tyne extend to 89 acres, at Grangemouth to 33, at Fleetwood to 15. On the south side of the Clyde, between Newark Castle and Langbank, the ponds extend for a distance of over 3 miles in length, some of them being 7 acres in area. They hold 1000 loads per acre. At Belfast the ponds are from 150 to 230 feet wide at water surface. The rafts at Grangemouth are generally 7 feet deep.

A vessel will discharge in the usual way from 150 to 260 logs a day; on the Clyde the cranes for discharging timber put out about 500 tons of timber a day.

[1] *Min. Inst. Civ. Eng.*, vol. xxi.

*Tonnage of the greatest British Ports.*—The following table shows the tonnage of British and foreign sailing and steam vessels that entered and cleared with cargoes at each port (from and to foreign countries and British possessions and coastwise) during the year 1884 :—[1]

| | ENTERED. | CLEARED. |
|---|---|---|
| *England*— | *Tons.* | *Tons.* |
| Barrow | 276,907 | 340,236 |
| Beaumaris | 594,230 | 645,047 |
| Bristol | 1,121,208 | 620,375 |
| Cardiff | 1,005,586 | 5,098,079 |
| Dover | 332,289 | 275,526 |
| Goole | 444,192 | 489,761 |
| Grimsby | 532,500 | 507,359 |
| Hartlepool | 416,198 | 762,722 |
| Hull | 1,813,422 | 1,521,554 |
| Liverpool | 6,955,293 | 6,485,323 |
| London | 11,345,542 | 5,884,610 |
| Middlesbrough | 489,811 | 878,729 |
| Newport | 739,494 | 1,784,730 |
| Plymouth | 797,963 | 475,786 |
| Rochester | 536,929 | 264,977 |
| Southampton | 1,190,119 | 792,359 |
| Sunderland | 349,497 | 2,610,511 |
| Swansea | 657,536 | 1,303,618 |
| Tyne Ports | 1,729,536 | 6,323,074 |
| *Scotland*— | | |
| Aberdeen | 634,759 | 375,753 |
| Ardrossan | 187,072 | 281,850 |
| Dundee | 419,860 | 190,064 |
| Glasgow | 2,227,049 | 2,617,942 |
| Grangemouth | 448,928 | 456,802 |
| Greenock | 1,213,922 | 444,307 |
| Leith | 938,980 | 760,867 |
| *Ireland*— | | |
| Belfast | 1,762,301 | 1,215,620 |
| Dublin | 1,698,414 | 1,080,815 |
| Londonderry | 302,110 | 187,518 |
| Newry | 279,450 | 186,850 |
| Waterford | 521,737 | 417,707 |

*Tonnage of the United Kingdom for the Years* 1882, 1883, *and* 1884.—The following table gives the tonnage of vessels,

[1] *Annual Statement of the Navigation and Shipping of the United Kingdom, year* 1884, p. 191.

including their repeated voyages, that entered and cleared with cargoes and in ballast at ports in the United Kingdom, from and to foreign countries and British possessions and coastwise for the years 1882, 1883, and 1884:—

| | Entered. | | | Cleared. | | |
|---|---|---|---|---|---|---|
| | 1882. | 1883. | 1884. | 1882. | 1883. | 1884. |
| | British Vessels. | | | | | |
| | *Tons.* | *Tons.* | *Tons.* | *Tons.* | *Tons.* | *Tons.* |
| Sailing vessels | 16,264,574 | 15,720,097 | 14,695,326 | 14,900,447 | 14,813,637 | 13,221,612 |
| Steam vessels | 45,690,212 | 49,618,885 | 50,387,594 | 41,851,082 | 45,303,114 | 46,258,593 |
| | Foreign Vessels. | | | | | |
| Sailing vessels | 5,662,466 | 5,146,816 | 4,503,828 | 5,573,243 | 5,106,697 | 4,564,514 |
| Steam vessels | 4,236,960 | 4,854,799 | 5,237,015 | 4,201,320 | 4,729,412 | 5,131,893 |
| | 71,854,212 | 75,340,597 | 74,823,763 | 66,526,092 | 69,452,860 | 69,176,612 |

*Lighthouses.*—Every port should be provided with a lighthouse for showing the exact position of the entrance during night; and where there are outlying rocks there should be leading lights, which, when kept in one line, conduct the mariner clear of all dangers. Harbour lighthouse towers may be of iron, masonry, or concrete; and, as a rule, lights on poles should be avoided. For a full description of the different forms of apparatus, whether dioptric or catoptric, I must refer the reader to works specially devoted to the subject.[1] All lighthouse apparatus, however, in order to collect and utilise the whole of the rays, should consist either entirely of glass acting by refraction and total reflection, or else of a union of

[1] *Rudimentary Treatise on the History, Construction, and Illumination of Lighthouses.* By Alan Stevenson, LL.B., F.R.S.E. London, 1850. *Lighthouse Construction and Illumination.* By Thomas Stevenson, F.R.S.E., F.G.S. *M. Inst. C. E.* London, 1881. *Optical Apparatus used in Lighthouses.* By J. T. Chance, M.A. *Min. of Proc. Inst. Civil Engineers*, vol. xxvi.

instruments of glass and metal acting by refraction and ordinary metallic reflection. Great annual loss of oil is too often entailed on harbour trustees by the use of optical apparatus which has not been designed to meet the special wants of the locality where it is placed. In one instance, the reflectors formerly in use being replaced by a single "*holophote*" of small size, consisting of a lens with zinc reflector, not only gave a greatly more powerful light, but has saved, according to the superintendent's returns, *two-thirds* of the oil formerly consumed. In another case where the light required to be spread over an *azimuthal* angle of 100°, one-half of the oil has been saved, and a far better and more equally distributed light produced by a small *azimuthal condensing apparatus* of glass.

*Lighthouse Apparatus.*—The superiority of the dioptric system is even more conspicuous at small harbours than in large sea-lights, for at the latter there is always a sufficient

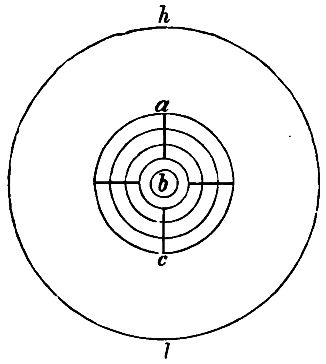


Fig. 35.

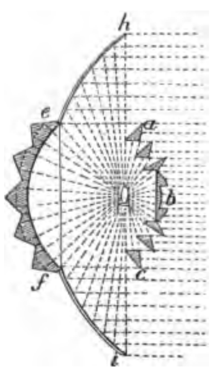


Fig. 36.

staff to keep the reflectors in proper polish, but this is very rarely attained in harbour lights. Some years ago I designed small dioptric apparatus and condensing lights of only 6

inches internal diameter, which are applicable alike for harbour, steamer, and railway purposes. Figs. 35 and 36 show in elevation and section a catadioptric holophotal apparatus for operating on the whole 360°, both in altitude and azimuth, so as to produce a single beam of parallel rays; *a b c* is a dioptric half-holophote, subtending a spherical angle of 180° at the flame; *e f* is a sector of a dioptric spherical mirror;

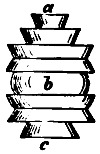


Fig. 37.

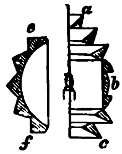


Fig. 38.

*h e f i* is a portion of a paraboloid. Figs. 37 and 38 represent the arrangements adopted, excepting that, instead of the dioptric spherical mirror which is shown behind, mirrors of silvered copper have often to be used from motives of economy.

Where the light admits of being condensed, the straight prisms of the forms suited to the given azimuthal arc are fixed outside of the other apparatus, so as to intercept the emergent rays, and thus to condense the whole 360° in altitude and azimuth into any required azimuthal arc. Plate XXIV. shows a condensing light for ships in side elevation and middle horizontal section, in which A*a* A is 180° of fixed light apparatus, *p p* straight condensing prisms, H spherical mirror. This design distributes all the rays with strict equality over 112° 30′, being the arc prescribed by the Board of Trade regulations. In order to give a steady light the apparatus and burner are hung on gymbals. In 1851, in order to reduce the cost, I had made for the harbour of Morecambe, Lancashire, a holophotal apparatus, the lenticular part of which

consisted of glass pressed into iron moulds, instead of regularly ground glass prisms. This economic arrangement has since been adopted by M. Degrand of Paris, who at the same time reduced, to a considerable extent, the thickness of the glass. I have lately had azimuthal condensing apparatus constructed on this plan for steamers' side lights, and although there is necessarily a loss of light, as compared with properly ground and polished lighthouse prisms, it is still, on economic considerations, very suitable for small habours. In order to equalise the power of the green light on the starboard side to that of the red light on the port side of steamers, the apparatus for the green light should be made of a larger size than for the red, so as to lessen the loss of light by divergence. By adopting a larger size of apparatus and a larger burner the power of the light is increased without causing increase of loss by divergence.

*Apparent Light.*—There are two kinds of light to which it may be useful to refer, from their being specially applicable to harbour purposes. The borrowed, or *apparent light* as I have termed it, is a simple means of illuminating a sunk rock or other danger which is inaccessible in stormy weather. This object is attained without requiring a lamp or any kind of flame to be placed on the rock itself. A beacon or perch, carrying on its top a lantern containing suitable forms of optical agents (depending on the nature of the local requirements), is all that is needed on the rock itself. A beam of parallel rays, proceeding from a distant holophote placed on the shore, is thrown seawards upon the lantern on the perch, where the incident rays are redispersed by the apparatus, so as to produce an optical deception to the eye of the mariner, who supposes he sees a lamp burning where there is in reality none. The apparent light is also very suitable for marking the seaward

ends of breakwaters or piers. In entering harbours, sometimes one pier-head must be hugged, sometimes the other, according to the direction of the wind; and so critical in stormy weather is the taking of a harbour, that even a single yard of distance may be of consequence. Those only who know, from personal experience, the anxiety that is felt on entering a narrow-mouthed harbour by night, when there is a heavy sea running, can fully appreciate the importance of descrying, at as great a distance as possible, the *exact* position of the weather pier-head. But pierhead lights are, from their exposed position, often inaccessible in stormy weather. At some places, too, the

Fig. 39.

outer breakwaters are not connected with the shore, and can only be reached by a boat in fine weather. The efficiency of an apparent light in such cases of difficulty has been fully tested at the entrance of Stornoway Bay, in the Island of Lewis, shown pictorially in Fig. 39, where it has been in use for the last thirty-four years, and has been favourably reported on by the captains of many vessels that have run for the anchorage at night. The beacon or perch, surmounted by the apparent light apparatus (which distributes the rays that fall upon it over an azimuthal angle of 62°), is placed on the Arnish rock, a sunk reef lying in the entrance to the bay,

while the light which illuminates this beacon is placed on thé land, at a distance of 530 feet. Figs. 40 and 41 show the apparatus on the perch given in section and elevation.

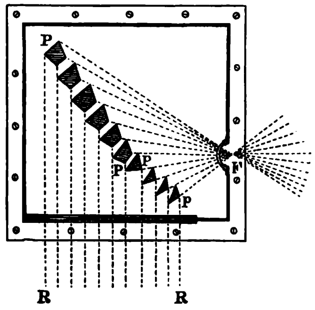



Fig. 40.

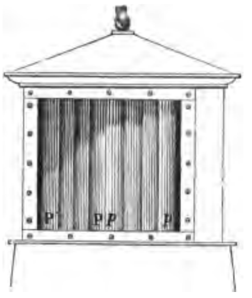



Fig. 41.

*Submarine Gas Pipes.*—In 1851 I suggested, though disapproving of it for certain situations, that gas pipes might be laid out to any inaccessible place, the position of which required to be marked by night. Admiral Sheringham, without any knowledge of my suggestion, experimented most successfully in 1853, in illuminating a buoy by means of gas. A light on this principle has also since then been constructed on the Clyde, near Port-Glasgow, at a distance of 300 feet from the shore, and is found to answer well. The gas, which is kept constantly burning, though with a very low flame during the day, is raised at night and lowered in the morning by stopcocks which are placed *on the shore.* To prevent any irregularity in the gas supply through pipes laid in the bed of a river, or in the sea, it has been suggested that the gas might be thoroughly dried by chloride of calcium.

*Pintsch's Gas Buoys.*—Pintsch's illuminated gas buoys form an important means of marking dangers by night. These buoys are made of wrought-iron, capable of standing a

pressure of 90 lbs. on the square inch, and of holding a supply of compressed gas, manufactured from crude shale oil, to last from about six weeks to two months according to size. Supported on iron standards attached to the top of the buoy, at an elevation of about 12 feet above the water, there is a lantern, in which is placed the burner surrounded by a small dioptric apparatus. A constant pressure is kept on the jet by a regulator, the flame burning day and night until the supply is nearly exhausted, when the buoy is recharged by a barge coming alongside with a reservoir of gas. These buoys have been successfully tried in an exposed situation in the Firth of Forth, and have been for some time past in use at the Clyde and at other places. If combined with the Courtenay automatic sound buoy they would at the same time be effective during fog. Compressed gas can also be applied to beacons where the exposure is not such as to prevent the gasholder being recharged at stated periods, all that is required being a reservoir of sufficient capacity—a burner, a lantern, and apparatus. The Gantock's beacon in the Clyde is about to be lighted in this manner. For pier-heads which are not accessible in certain states of the weather compressed gas may also be applied with advantage.

*Flashing Meter.*—Where compressed or ordinary coal gas is used I proposed to distinguish one buoy or beacon from another by making the flow of the gas produce automatic intermittent action by means of a dry meter. Such a meter must always pass a sufficient quantity of gas to secure the constant burning of a small jet, situate either immediately above or in the socket of a larger burner provided with a separate tube, for giving at regular intervals an increased supply which goes to the main burner, and is there ignited by the small jet. The full flame continues to burn until the

action of the meter cuts off the larger supply, and the small jet is again left burning alone. This process will, of course, go on continuously so long as the gas in the buoy is not exhausted. This meter is applicable for producing intermittent lights on land or on beacons, but more extended experiments are yet required to prove its suitability for floating buoys. If colour in addition to intermittent action be adopted, varied distinctions may be produced.

Major G. L. Gillespie[1] describes a simple mode of showing a temporary light at inaccessible stations when works are in progress, which, as it may be useful in some situations, we shall transcribe :—

"As soon as the ice began to form in the river I found it impracticable to communicate with the floats, and as the continued use of the harbour by ice vessels from the upper lakes rendered it advisable to keep up a display of the light, I resorted to an expedient for lighting the outer cribs, which I have successfully used to the present time. The device consists of an endless wire connecting a shore station on the old north pier with a mast 22 feet high, framed into the end of the last crib, over which a lantern is passed through the medium of an iron frame. The distance between the stations is 600 feet. The lantern is attached directly to the frame so as to be kept upright in position, and in turn the lower part of the frame is lashed firmly to the lower branch of the wire, and the upper part is fashioned into a ring through which the upper wire passes. The wire is $\frac{1}{4}$ inch diameter, 1200 feet long, and is supported at both stations upon sheaves, and the lantern is run out and in by means of a crank attached to the axis of the inner sheave. The time of passage of the lantern between the stations is about two minutes."

[1] *Annual Report of the Chief of Engineers, Year* 1876. W shington, 1876, p. 427.

*Electric Spark.*—I have tested a proposal which I made in 1851 for illuminating beacons or pier-heads by means of electricity conveyed through submarine or suspended wires connected with the shore. The induction spark is produced in the focus of optical apparatus. The cost of producing the light, and the difficulty in certain localities of maintaining the wire, has hitherto prevented its introduction.

In all Provisional Orders and Acts for harbours, the Board of Trade inserts clauses providing for the exhibition of lights, and the three general Lighthouse Authorities now inspect all harbour and local lights once in three years, the results of such inspections being laid before Parliament.

*Advantages of Government Supplementing Local Funds.*—In concluding these remarks on harbours, it may not be out of place to state that the want of sufficient funds occasions a great national loss in the construction of many of our ports. The history of a large number of works which have been erected by private or local enterprise presents a record of the building of piers at one period when funds were small, and of taking them down again at another when the trade had increased and more room and accommodation were required. The difficulty of procuring capital for schemes, however beneficial in their tendency, and however likely to be ultimately productive, is fully established by the early history of many of our now flourishing ports.

Mr. Webster justly affirms on this subject "that if it be a true principle of commercial policy that docks should be in advance of the actual wants of trade, that stations should be freely afforded on the highway of the seas in which the products, artificial and natural, of all nations may be collected for interchange and distribution, it follows that capital must be employed on an object which, for the time being, or on a

limited view of the case, may be regarded as unproductive; and hence arises the difficulty, in questions of this nature, of providing ample dock accommodation for a rapidly-increasing and variable state of commerce at the minimum rate of charge consistent with profitable investment. The history of the dock estate of Liverpool, and of the struggles and questions to which its constitution has necessarily given rise, will afford curious illustration of the difficulties with which this question is surrounded."[1]

The want of sufficient funds often prevents the original works being carried into deep water, and, in consequence, the most expensive part of the protecting breakwater is put down just in the very place which has afterwards to be converted, at great expense, into a deep-water access or berthage. Sometimes, indeed, a whole line of pier is, from motives of economy, placed in such a manner as to interfere most materially with what might have been by far the best and safest berths for shipping, so that in the future extension of the works part of the old harbour has to be demolished. Want of a proper marine survey has also led to very serious errors in the position of piers. It is most important, therefore, that in all designs for harbours the principle of making improvements and extensions *anticipative* should be clearly kept in view.

To such an extent has this system of partial and limited improvements prevailed, that were an engineer called on to value many of our works as they exist at present, his estimate, however fairly and fully made out, would fall far short of the actual cost. For it would proceed on a measurement of what he sees, while the actual cost would include the building of

[1] *The Port and Docks of Birkenhead.* By T. Webster, M.A., F.R.S. London, 1848.

piers and jetties which had ceased to exist. For these reasons, we conceive there could hardly be a more advisable expenditure of the public money than a system of grants, on a liberal scale, for supplementing the local funds. With such aid the authorities on the spot would be enabled to protect and improve the existing physical advantages which the shores possess, by preventing the construction of proposed improvements on too narrow a scale. But a comparatively slight increase of the means would, in many instances, inclose a great additional area, and secure a deeper access with superior internal tranquillity; the want of which cripples the trade, and becomes a subject of lasting regret to all frequenting the port.

It is gratifying to add that, since the above remarks regarding Government aid appeared in the article "Harbours" in the *Encyclopædia Britannica*, the Act of 1861 was passed, and was intended to encourage a system of loans under £100,000, of public money in aid of harbour construction, at the rate of 3¼ per cent interest, for periods not exceeding fifty years. By the Public Works Loans Act 1879 (42 & 43 Vict. c. 77), and the Treasury Minute thereon, the following scale was substituted for the 3¼ per cent interest, viz.—

3½ per cent on loans repayable within a period not exceeding twenty years.
3¾ per cent on loans repayable within a period not exceeding thirty years.
4 per cent for loans repayable within a period not exceeding forty years.
4½ per cent on loans repayable within a period not exceeding fifty years.

Since the passing of the Act of 1861, the Loan Board has advanced, up to 31st March 1883, £2,561,849, of which £694,505 has been repaid. The Select Committee on "Har-

bour Accommodation," in their Report of 22d July 1884, recommended "that harbours selected on grounds of public policy for these loans at a low rate of interest, should be given the full benefit of the credit of the State, and have the money required advanced to them at the lowest possible rate of interest, certainly not exceeding 3½ per cent, the repayments being provided for by means of a sinking fund extending over fifty years."

# REFERENCE TO PLATES.

PLATES

I., II., and III. Represent different modes of finishing pier-heads, and of terminating talus walls at various harbours. The arrows denote the directions in which the heaviest waves strike the piers.

IV., V., and VI. Cross-sections of different tidal piers of masonry.

VII. Cross-sections of Kilrush, Dover, Cherbourg, Kingston, and Plymouth Breakwaters.

VIII. Cross-sections of the south and north piers of the Tyne, kindly furnished by Mr. Messent. The South Gare Breakwater, Tees, kindly supplied by Mr. Fowler; also sections of the Genoa, Alderney, Portland, and Holyhead Breakwaters.

IX. Cross-sections of jetties of timber at Dunkirk, Invergordon, and Blyth.

X. Cross-sections and elevations of timber jetties at Londonderry, Nairn, and Leith.

XI. Wick Bay and Breakwater, and the monolithic block of 1350 tons, which was dislodged and removed by the waves.

XII. Is taken from a photograph, kindly furnished by Mr. Johnston of Wick, of the waves when striking upon the breakwater, the parapet of which is 21 feet above the sea.

XIII. Shows all the important British sea lighthouses hitherto constructed in exposed situations, drawn to the same scale, and referred to at page 123. The hard line drawn across the plate represents the level above high water of a spring tide, and the dotted line shows the level above high water at which the masonry was dislodged at the Dhuheartach Lighthouse, Argyllshire, and which is nearly the same as that of the open gallery of Winstanley's Lighthouse on the Eddystone.

PLATES

XIV. Gates of the Londonderry Graving Dock, as designed by Messrs. Stevenson. Fig. 1 shows elevation, Fig. 2 cross-section, Fig. 3 shows the mode in which the beams were formed of logs built together. The other diagrams show details of friction-roller, etc., as designed by Messrs. Rendel and Robertson.

XV. The Victoria Dock cylindrical gates, designed by the late Mr. G. P. Bidder, as given in the *Proceedings of the Institution of Civil Engineers.*

XVI. Figs. 1 to 9 show details of the dock gates, designed by the late Mr. J. M. Rendel for Great Grimsby. The drawings are from the *Minutes of the Institution of Civil Engineers.* Figs. 10 and 11 are the anchor plates of the Londonderry Dock gates, and Figs. 12 and 13 those of the gates at Great Grimsby.

XVII. Cross-section, half elevation, and half logitudinal section of the caisson of the Graving Dock at Cardiff, designed by Mr. John M'Connochie, C.E.

XVIII. Represents in plan and cross-section the Graving Dock at Londonderry, erected in 1862, showing the system of underground drainage for keeping the floor dry.

XIX. Sections of the walls of Hornby and Langton Docks, Liverpool, kindly furnished by Mr. Lyster; the Royal Albert Dock, London; Glasson Dock, Morecambe Quay; Edinburgh Dock, Leith; and also in plan and section the Plantation Quay, and the new method of arranging the cylinders at Queen's Dock, Glasgow, kindly supplied by Mr. Deas.

XX. A cross-section of the breakwater at Aberdeen, by Mr. W. D. Cay; and a cross-section and plan of the North Pier of the Delta of the Danube, by Sir Charles Hartley.

XXI. A cross-section and plan of the western breakwater at Anstruther.

XXII. Plan and section of a tidal fishing harbour.

XXIII. Plan and section of an example of a Donegal pier.

XXIV. Condensing light for ships shown in side elevation and middle horizontal section.

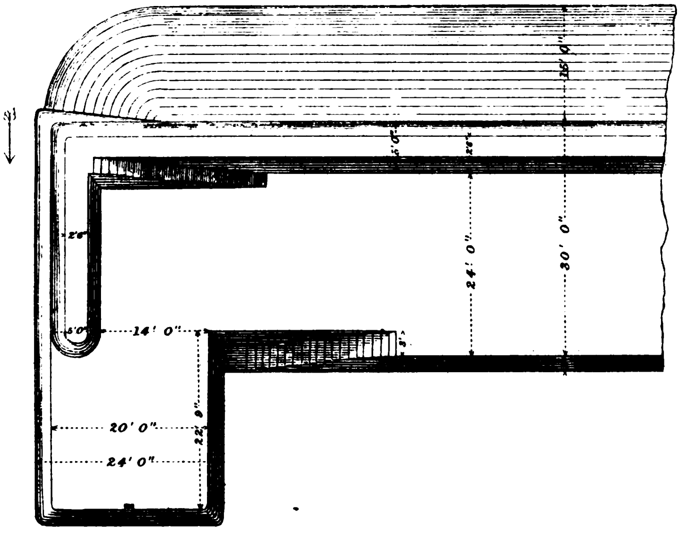
# INDEX.

THE END.

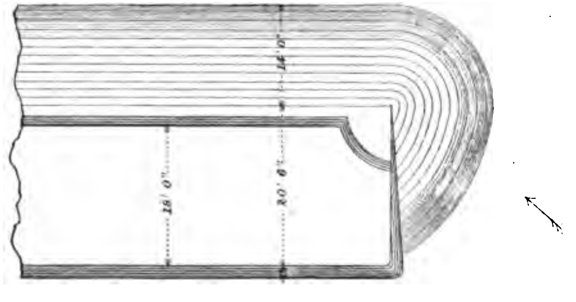
*Printed by* R. & R. Clark, *Edinburgh.*

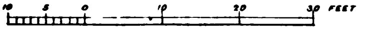
## PIER HEADS.

MULLAGHMORE, COUNTY OF SLIGO.
MESSRS STEVENSON, C.E. 1839.

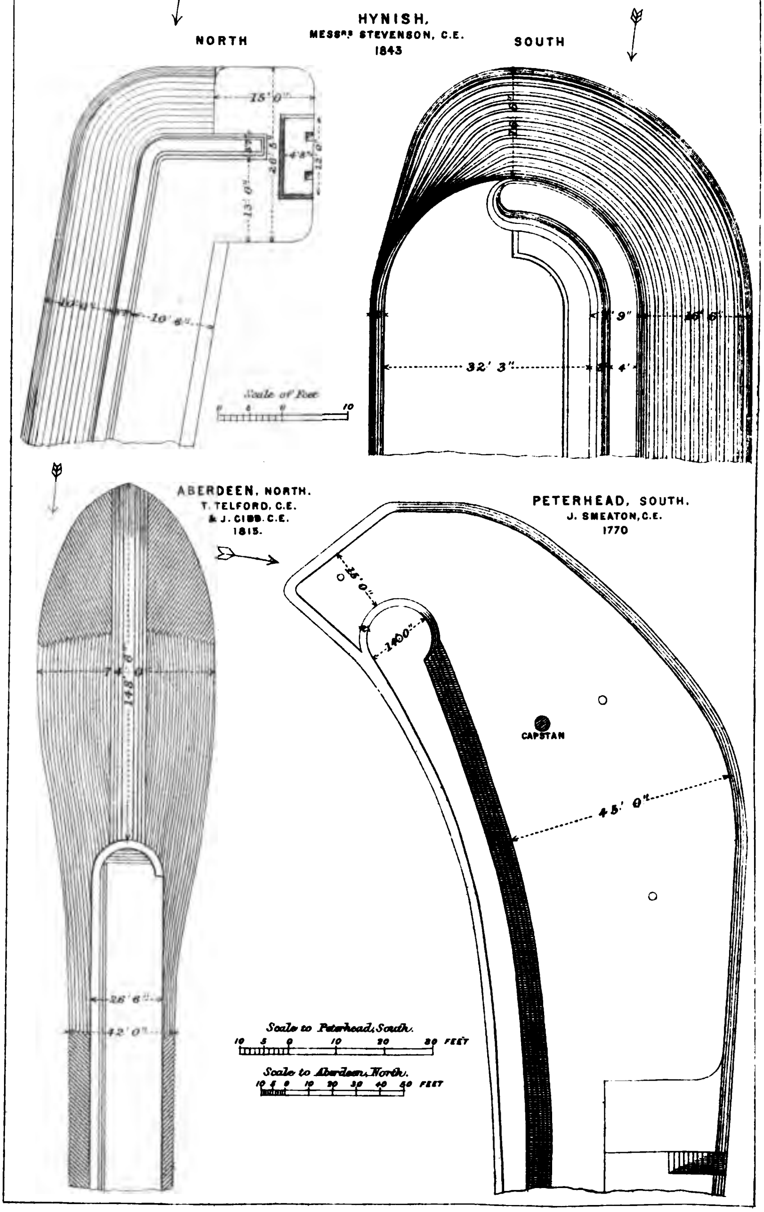



FISHERROW, COUNTY OF EDINBURGH.
MESSRS STEVENSON, C.E.

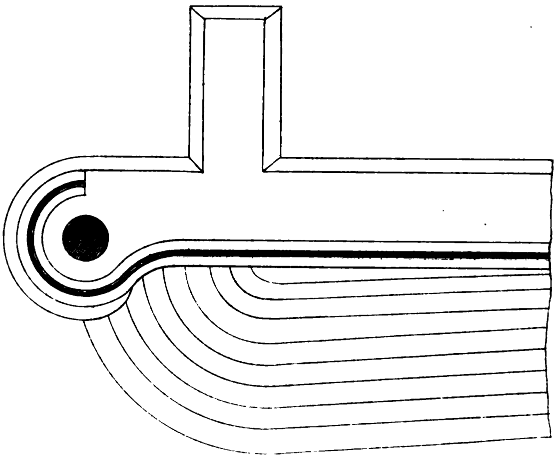


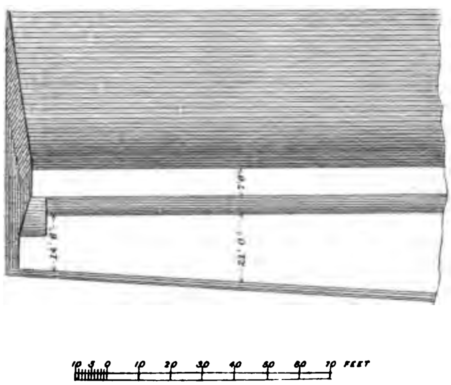
# PIER HEADS.


HYNISH.
MESSRS STEVENSON, C.E.
1843
NORTH
SOUTH
15' 0"
26' 3"
13' 0"
4' 6"
12' 0"
10' 6"
Scale of Feet
10
32' 3"
9"
4'
ABERDEEN, NORTH.
T. TELFORD, C.E.
& J. GIBB, C.E.
1815.
74' 0"
148' 0"
28' 6"
42' 0"
PETERHEAD, SOUTH.
J. SMEATON, C.E.
1770
15' 0"
14' 0"
CAPSTAN
45' 0"
Scale to Peterhead, South.
10 5 0 10 20 30 FEET
Scale to Aberdeen, North.
10 5 0 10 20 30 40 50 FEET

PORTPATRICK, COUNTY OF WIGTON.
J. RENNIE C.E.

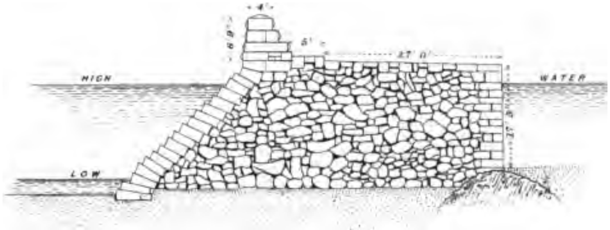


SARCLET. C° CAITHNESS.
J. MITCHELL C.E.
1833.

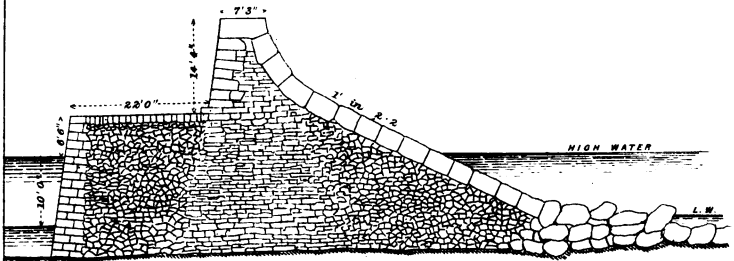


# CROSS SECTIONS.

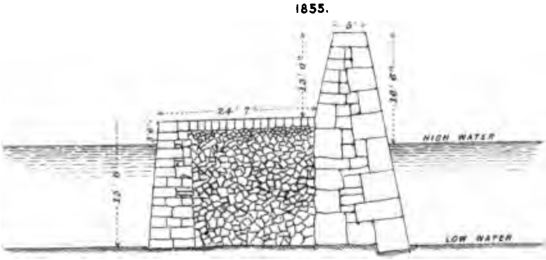
## HYNISH, ARGYLLSHIRE.
MESSRS STEVENSON C.E.
1843.

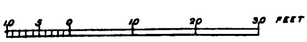



## OLD PIER OF WICK.
1823.



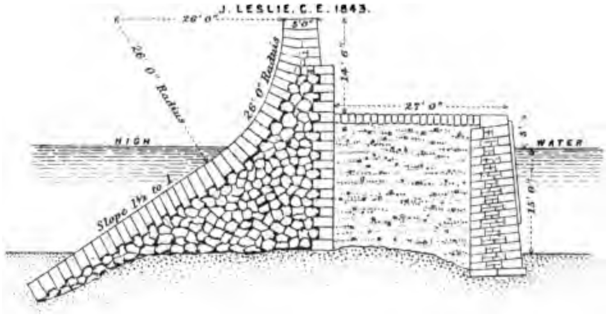

## NETHER BUCKIE.
D. & T. STEVENSON C.E.
1855.



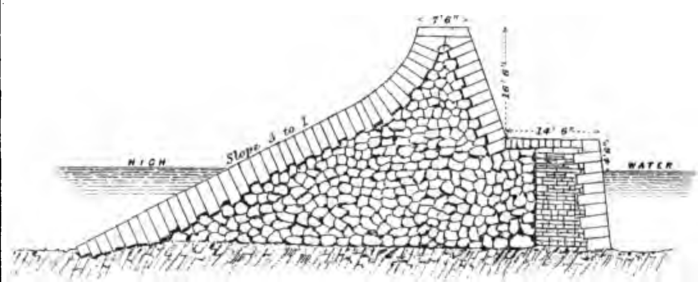



# CROSS SECTIONS.

KIRKCALDY - Cº FIFE.
J. LESLIE, C. E. 1843.



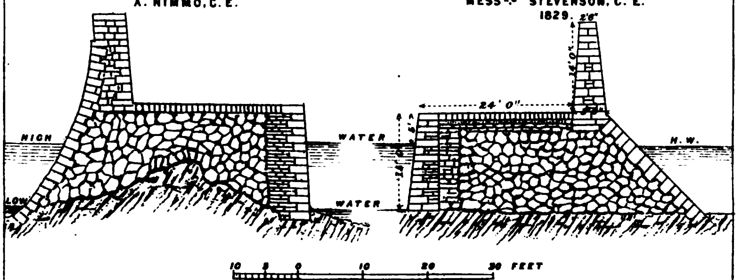

SARCLET - Cº CAITHNESS.
J. MITCHELL, C. E.
1833.



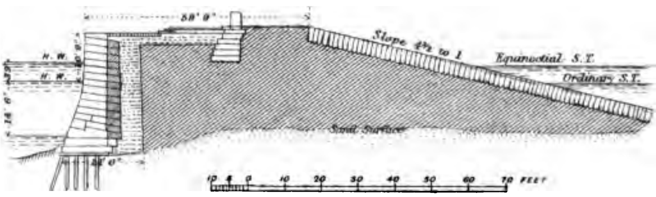

MULLAGHMORE - Cº SLIGO.

EAST PIER.
A. NIMMO, C. E.

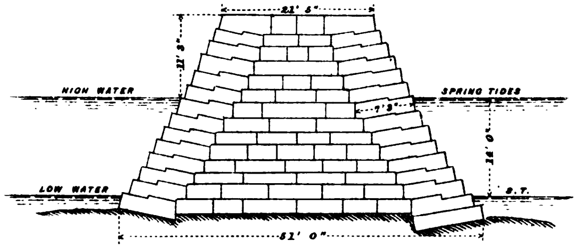
WEST PIER.
MESSʳˢ STEVENSON, C. E.
1829.



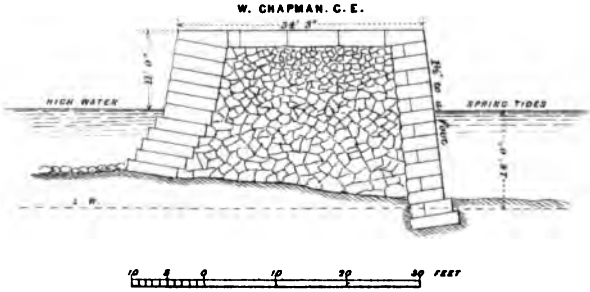
NORTH PIER, SUNDERLAND.




NORTH EAST PIER, SEAHAM,
EASTERN EXTENSION,
W. CHAPMAN, C. E.



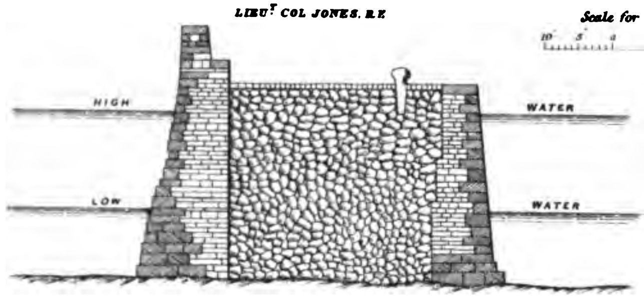

NORTH EAST PIER, SEAHAM.
W. CHAPMAN, C. E.



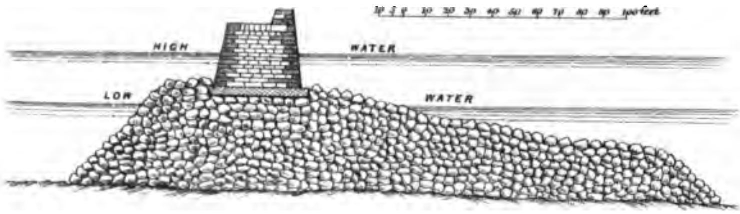
## KILRUSH

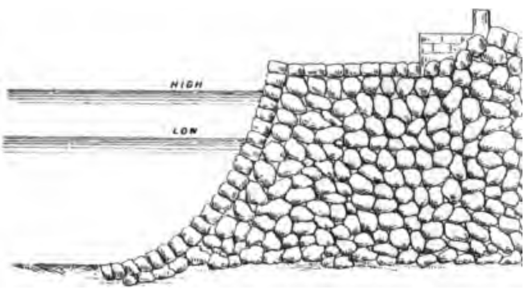
LIEUT. COL JONES, R.E.

Scale for Dove



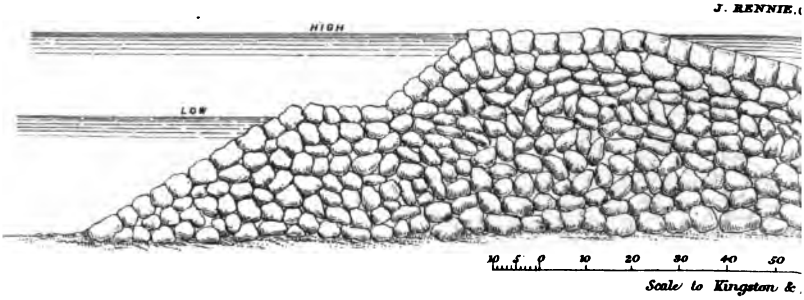

## CHERBOURG



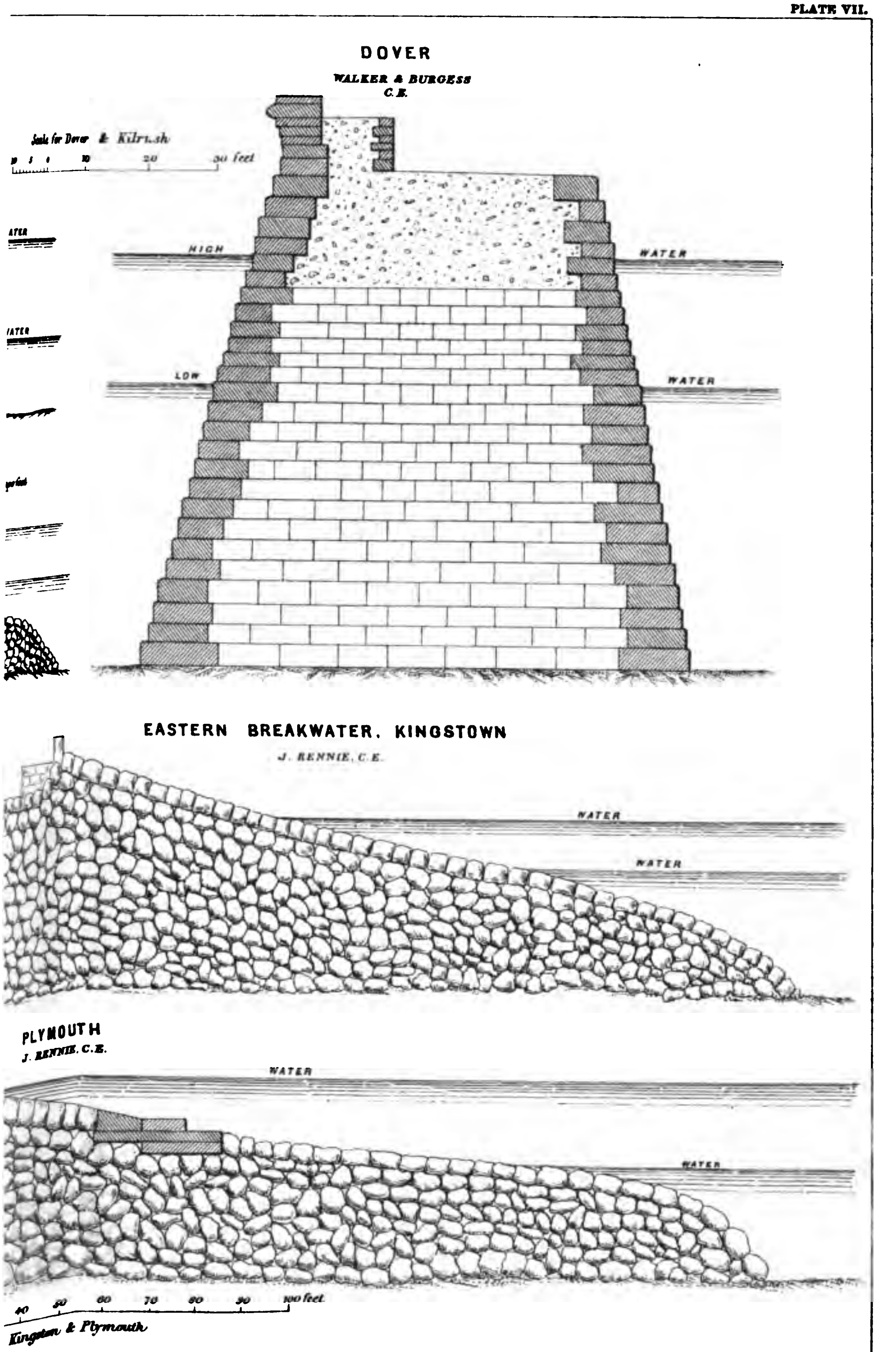

## PLYMOUT

J. RENNIE, (



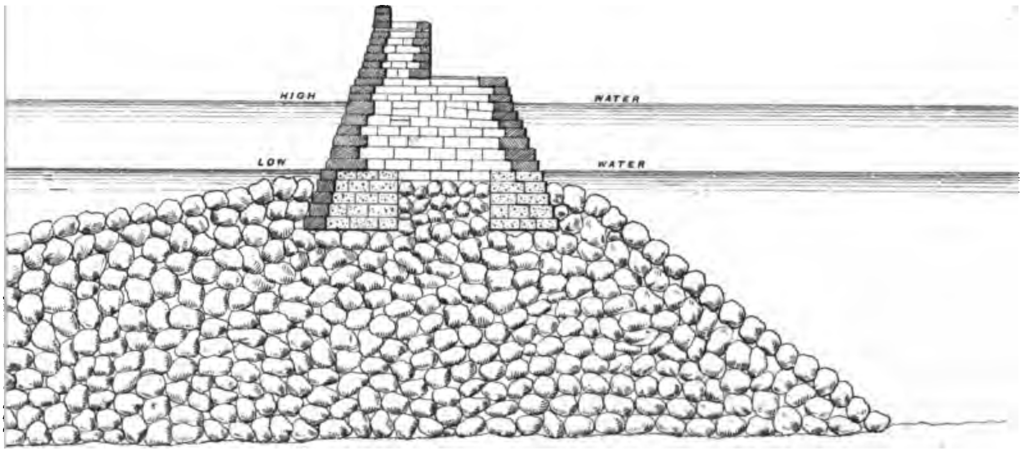

Scale to Kingston & 

PLATE VII.


DOVER
WALKER & BURGESS
C.E.
Scale for Dover & Kilrush
10
20
30 feet
HIGH
WATER
LOW
WATER
EASTERN BREAKWATER, KINGSTOWN
J. RENNIE, C.E.
WATER
WATER
PLYMOUTH
J. RENNIE, C.E.
WATER
WATER
40
50
60
70
80
90
100 feet
Kingston & Plymouth

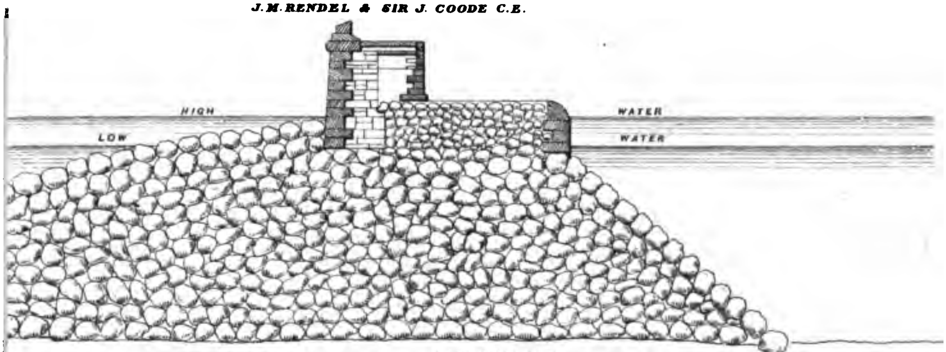
ALDERNAY

JAMES WALKER, C. E.



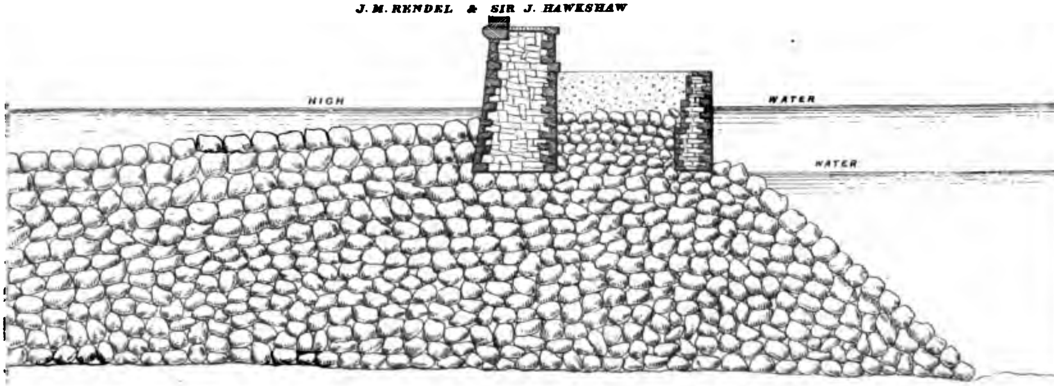

PORTLAND

J. M. RENDEL & SIR J. COODE C. E.

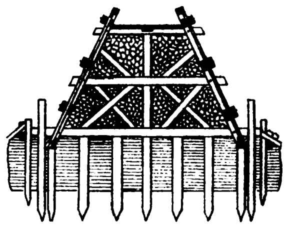



HOLYHEAD

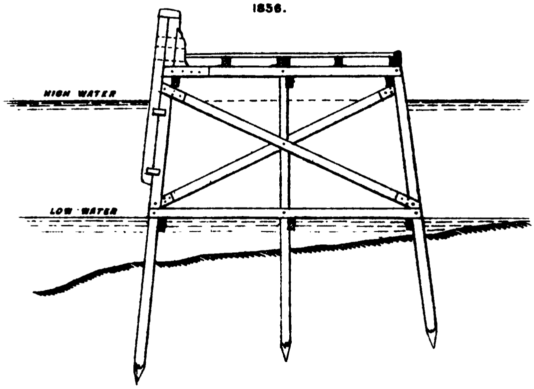
J. M. RENDEL & SIR J. HAWKSHAW



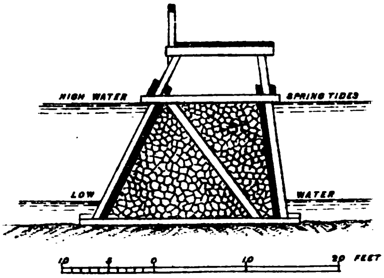
JETTY OF ANCIENT PORT OF DUNKIRK.
1699.



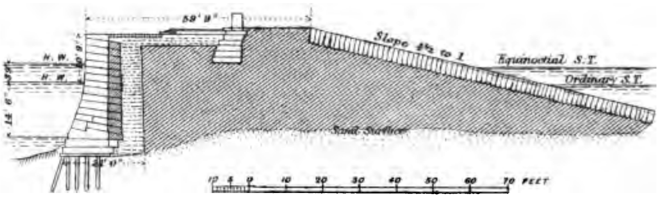
INVERGORDON JETTY.
D.& T. STEVENSON. C.E.
1856.



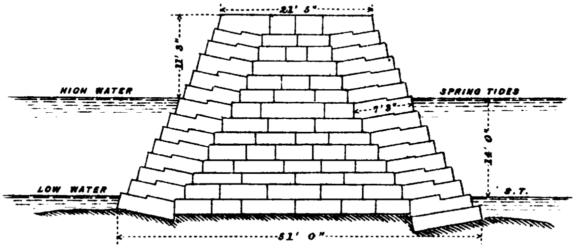

BLYTH BREAKWATER, J. ABERNETHY. C.E.
1856.



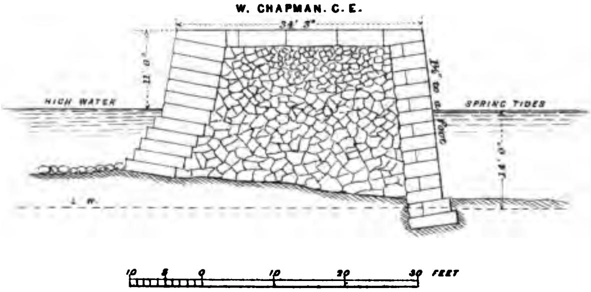
NORTH PIER, SUNDERLAND.

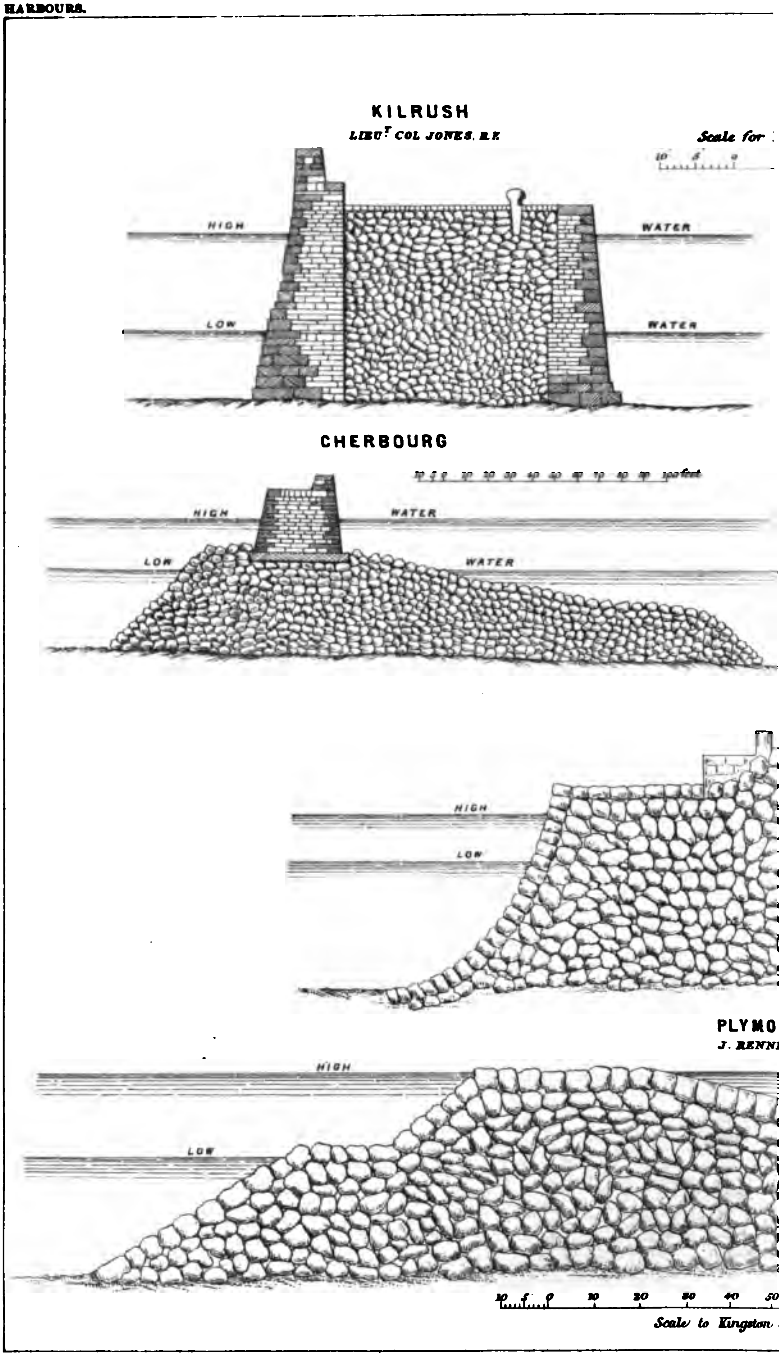


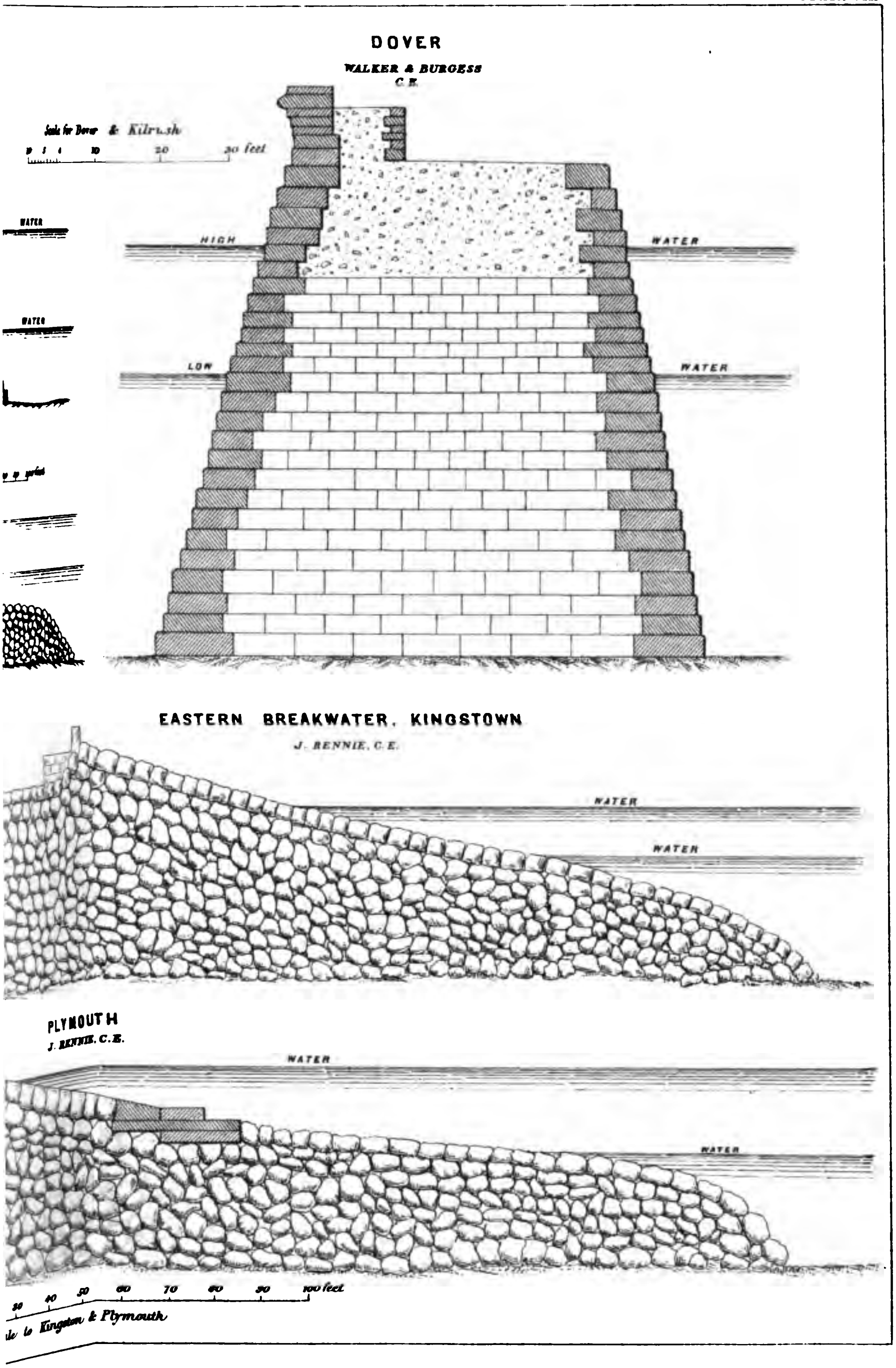

NORTH EAST PIER, SEAHAM,
EASTERN EXTENSION,
W. CHAPMAN. C. E.




NORTH EAST PIER, SEAHAM.
W. CHAPMAN. C. E.

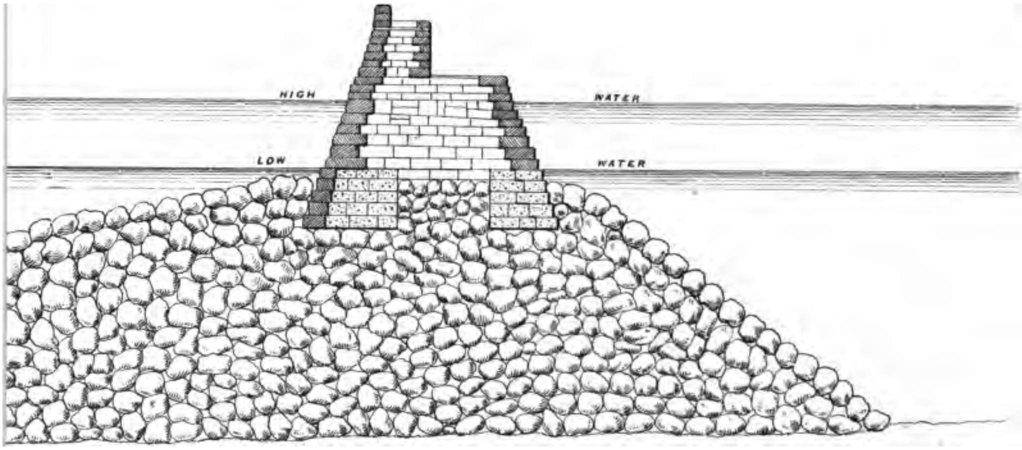



KILRUSH
LIEUT. COL JONES, R.E.
Scale for
10 5 0
HIGH
WATER
LOW
WATER
CHERBOURG
10 5 0 10 20 30 40 50 60 70 80 90 100 feet
HIGH
WATER
LOW
WATER
HIGH
LOW
PLYMO
J. RENN
HIGH
LOW
10 5 0 10 20 30 40 50
Scale to Kingston


DOVER
WALKER & BURGESS
C.E.
Scale for Dover & Kilrush
10 20 30 feet
HIGH
WATER
LOW
WATER
EASTERN BREAKWATER, KINGSTOWN
J. RENNIE, C.E.
WATER
WATER
PLYMOUTH
J. RENNIE, C.E.
WATER
WATER
30 40 50 60 70 80 90 100 feet

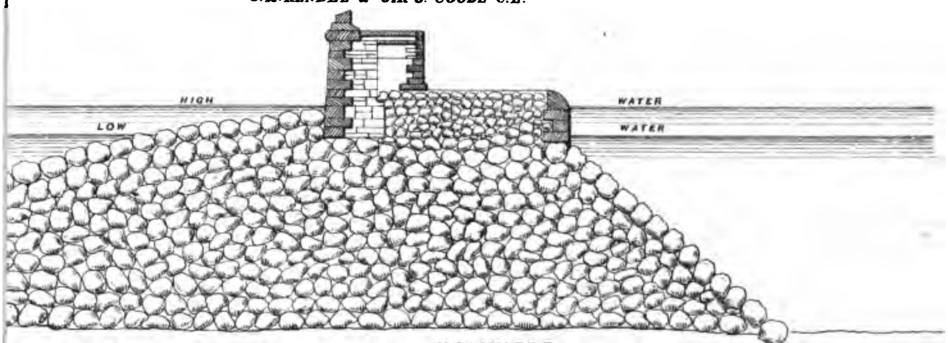
ALDERNAY

*JAMES WALKER, C. E.*



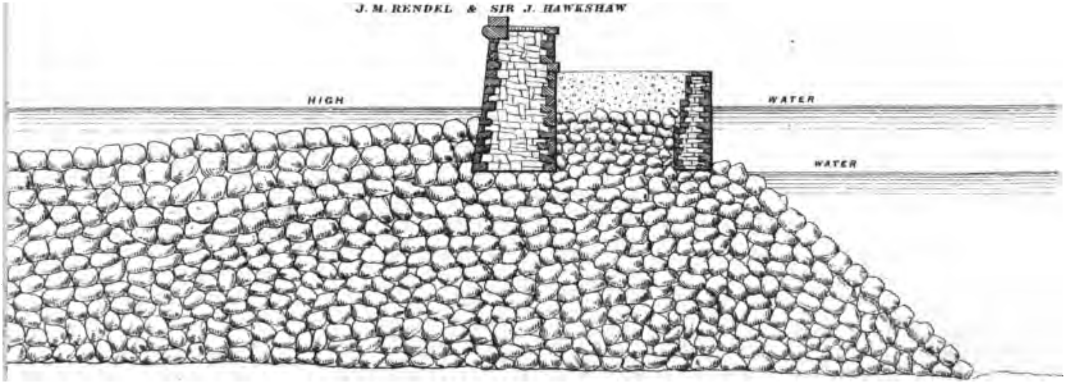

PORTLAND

*J. M. RENDEL & SIR J. COODE C.E.*

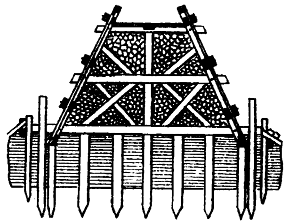



HOLYHEAD

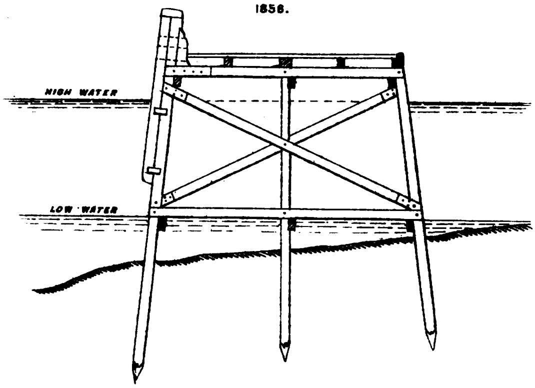
J. M. RENDEL & SIR J. HAWKSHAW



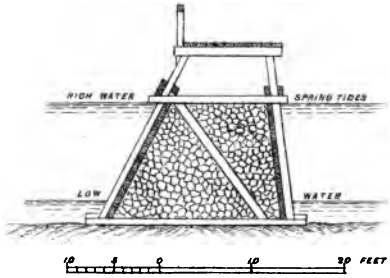
JETTY OF ANCIENT PORT OF DUNKIRK.
1699.

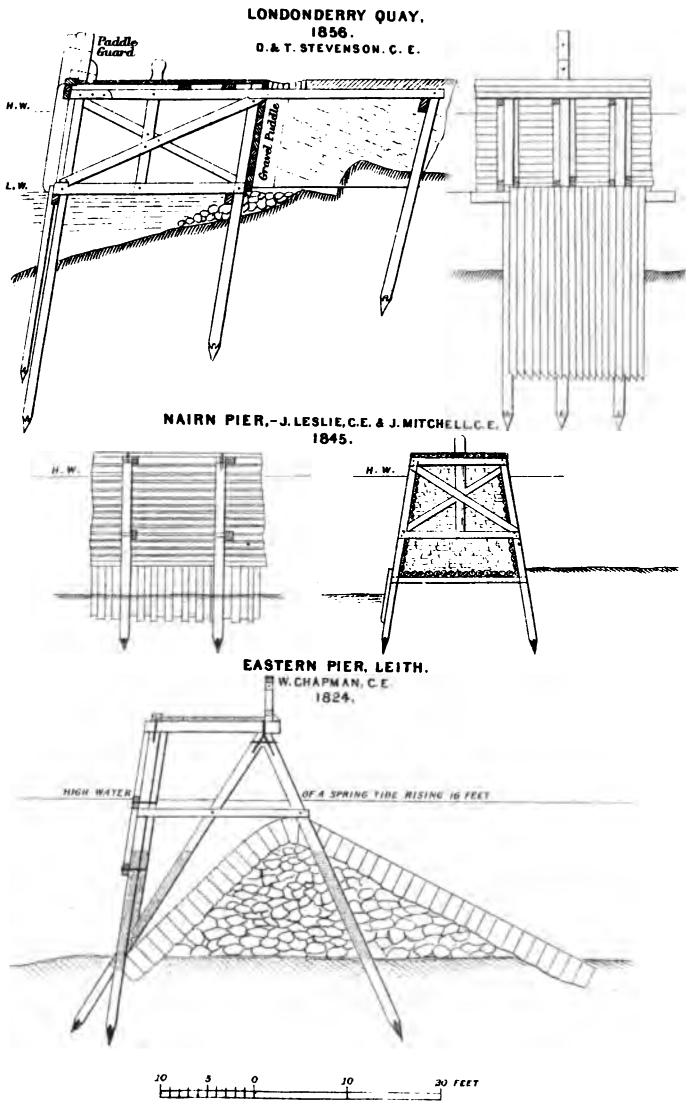


INVERGORDON JETTY.
D. & T. STEVENSON. C.E.
1856.

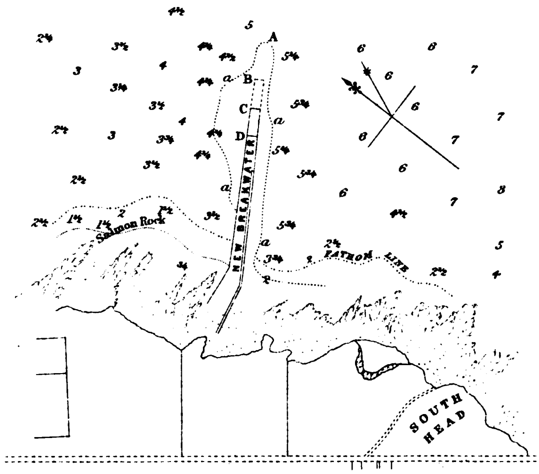



BLYTH BREAKWATER, J. ABERNETHY. C.E.
1856.




LONDONDERRY QUAY.
1856.
D. & T. STEVENSON. C. E.
Paddle Guard
Gravel Puddle
H.W.
L.W.
NAIRN PIER,–J. LESLIE, C.E. & J. MITCHELL, C.E.
1845.
H.W.
H.W.
EASTERN PIER, LEITH.
W. CHAPMAN, C.E.
1824.
HIGH WATER OF A SPRING TIDE RISING 16 FEET
10 5 0 10 30 FEET

# WICK BAY




NOTE *The depths are in Fathoms at Low Water Spring Tides.*

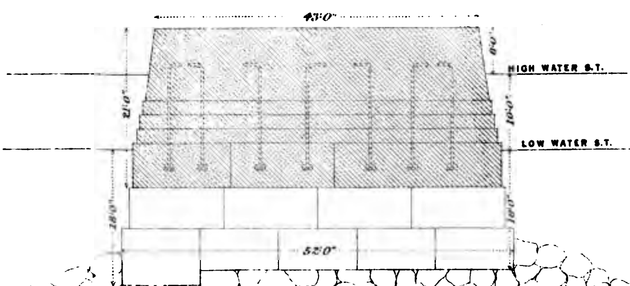
**REFERENCES**

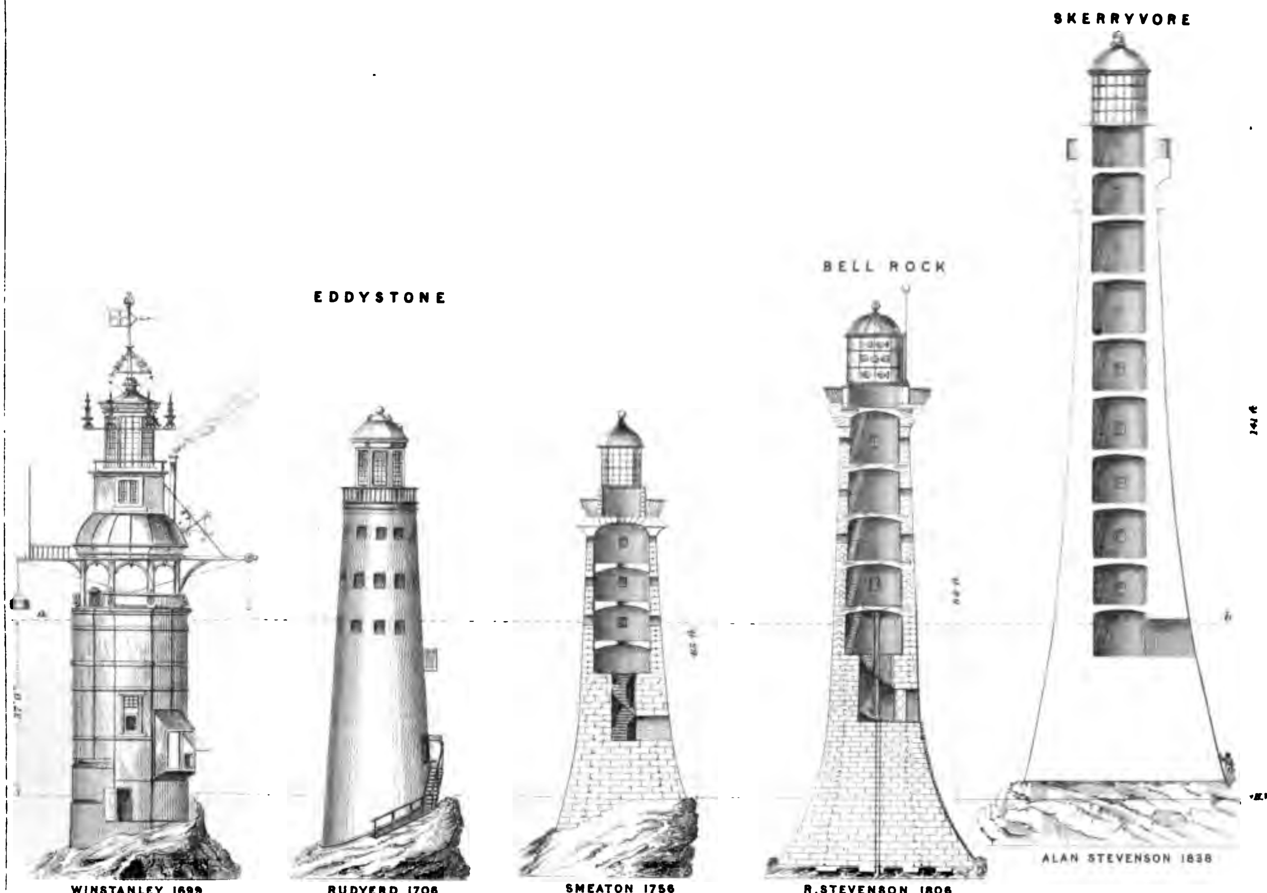
A. *Extreme distance to which the Rubble base was carried.*
B. *Extreme distance to which the superstructure was carried.*
C. *Point to which the building was restored & finished by Cement Blocks.*
D. *Present end of building left standing.*
*The dotted line a shews the extent of the Bay occupied by Rubble laid down from the Staging or spread by Storms as last ascertained after the damage of Feb<sup></sup>y 1870.*

SCALE
100 50 0 100 200 300 400 500 600 700 800 900 1000 Feet

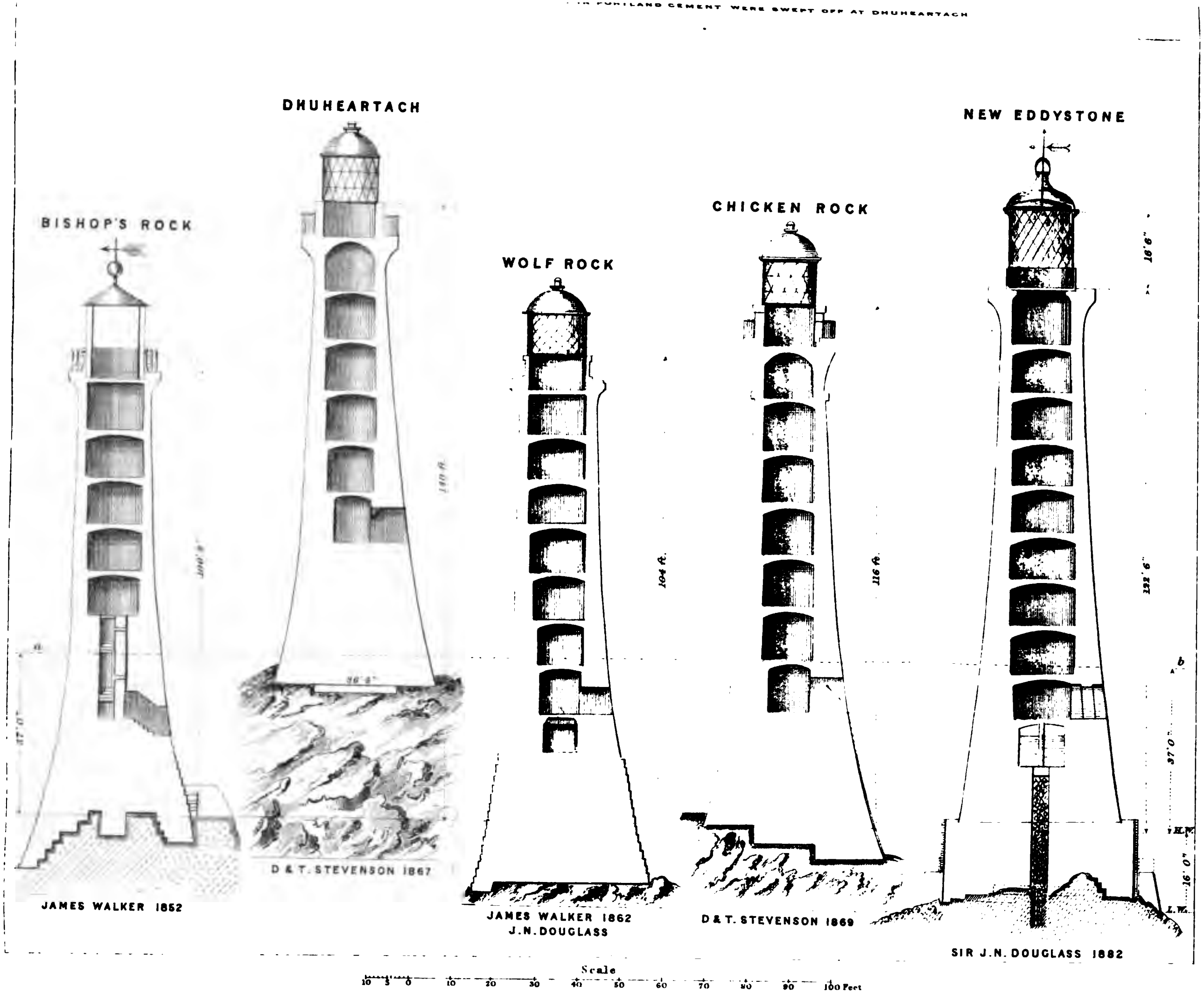
*Elevation of the end of the Breakwater shewing in diagonal shade lines the Mass of 1350 tons which was removed entire and the manner in which it was connected together by iron bars.*

SCALE
10 5 0 10 20 30 40 Feet






*a. b.* HEIGHT AT WHICH 14 JOGGLED STONES SET IN PORTLAND CEMENT, WERE SWEPT OFF AT DHUHEARTACH.



BISHOP'S ROCK
DHUHEARTACH
WOLF ROCK
CHICKEN ROCK
NEW EDDYSTONE
100' 0"
37' 0"
120 ft.
36' 0"
104 ft.
116 ft.
16' 6"
122' 6"
37' 0"
16' 0"
H.W.
L.W.
JAMES WALKER 1852
D & T. STEVENSON 1867
JAMES WALKER 1862
J.N. DOUGLASS
D & T. STEVENSON 1869
SIR J.N. DOUGLASS 1882
Scale
10 5 0 10 20 30 40 50 60 70 80 90 100 Feet

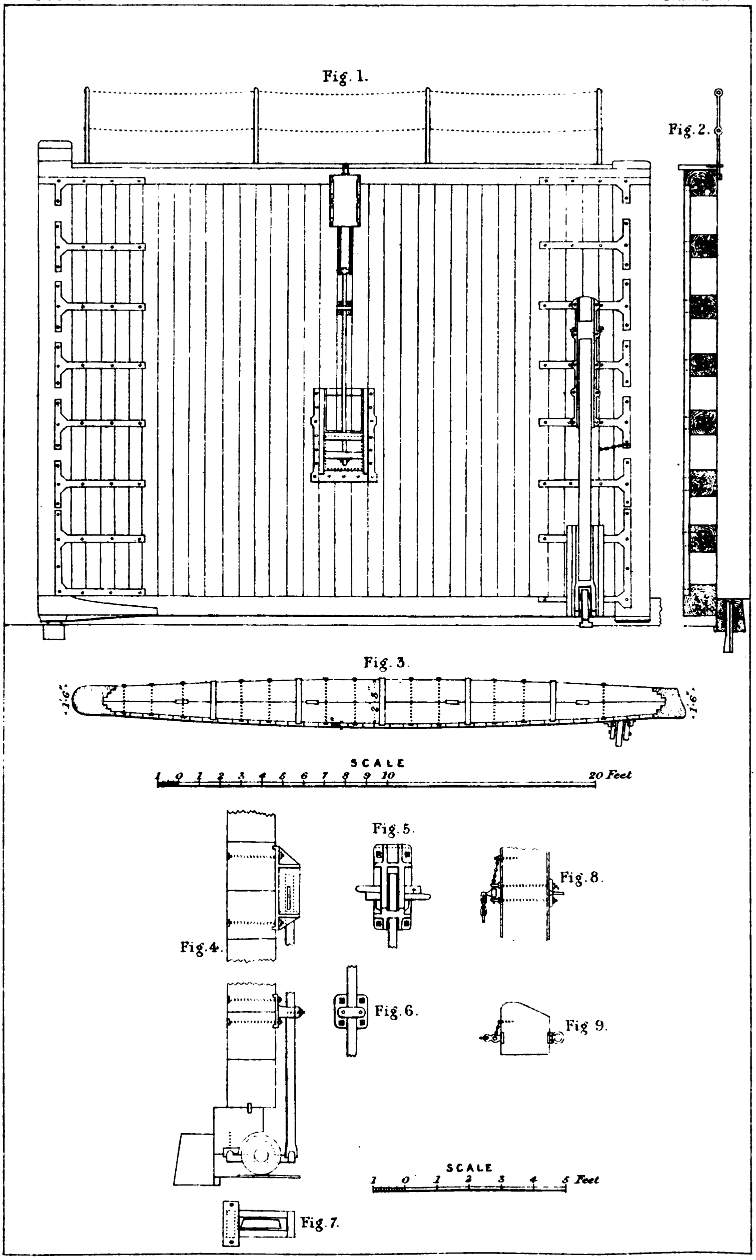
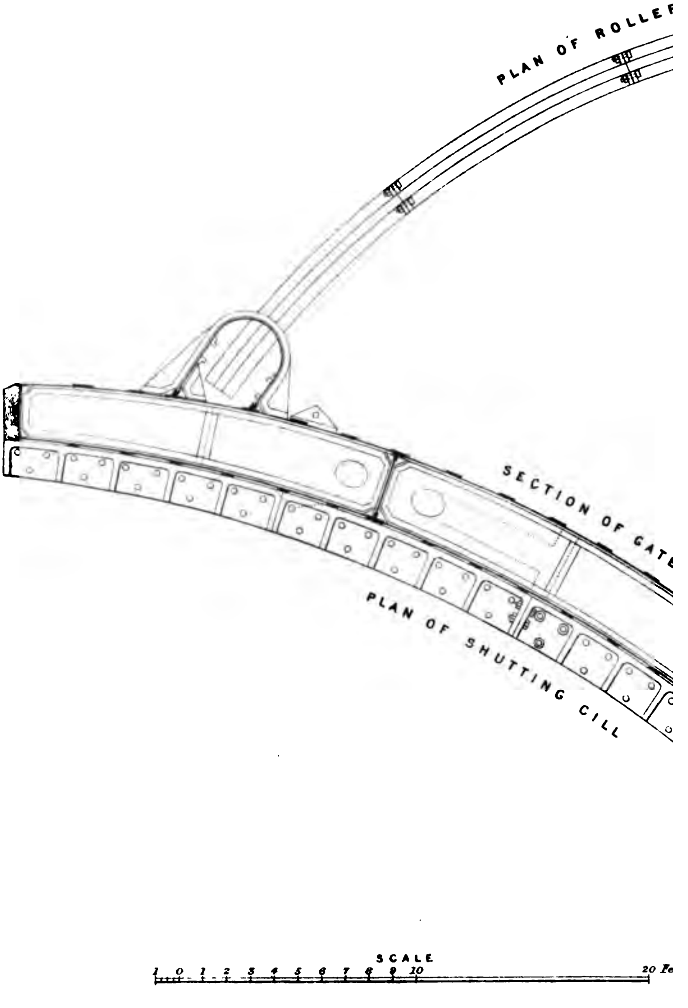
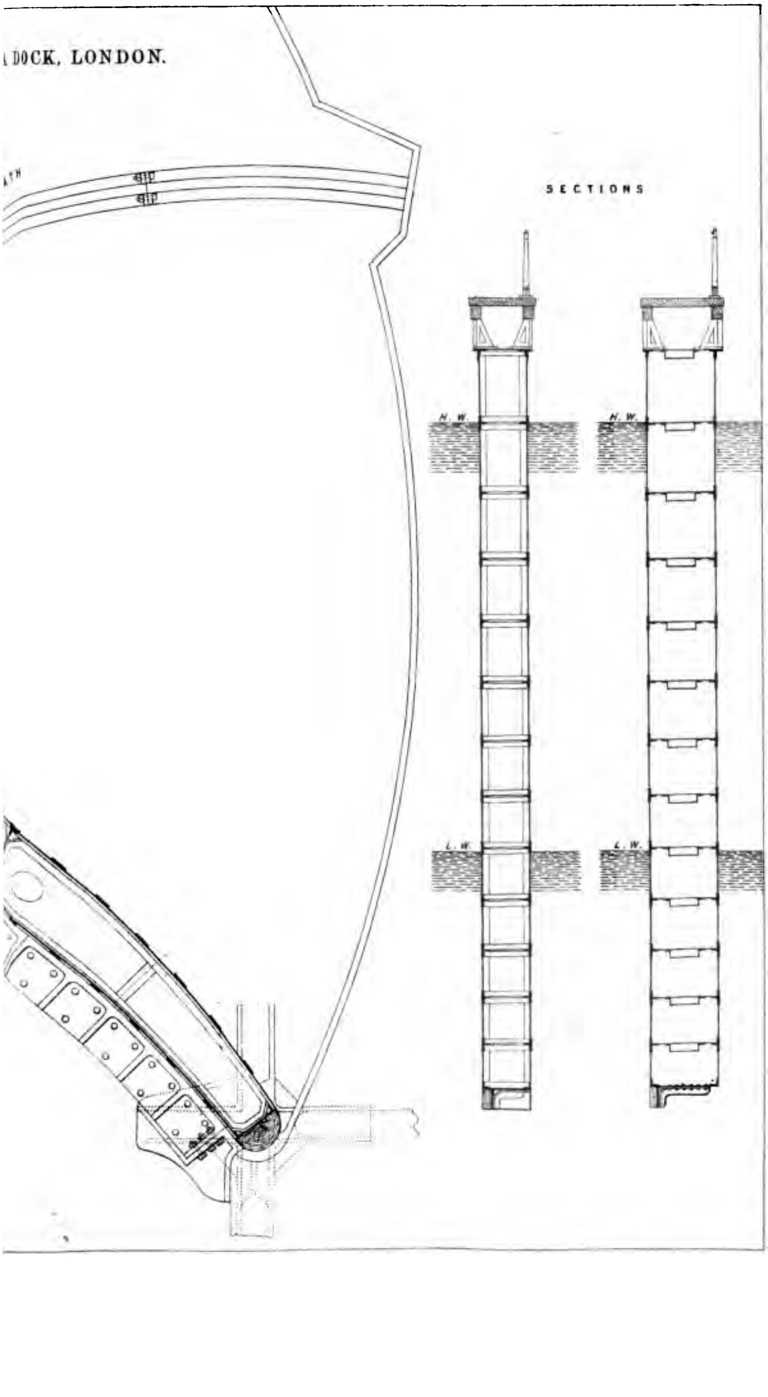


Fig. 1.
Fig. 2.
Fig. 3.
1'6"
2'8"
1'6"
SCALE
1 0 1 2 3 4 5 6 7 8 9 10 20 Feet
Fig. 4.
Fig. 5.
Fig. 6.
Fig. 7.
Fig. 8.
Fig 9.
SCALE
1 0 1 2 3 4 5 Feet

VICTO


PLAN OF ROLLEF
SECTION OF GATE
PLAN OF SHUTTING CILL
SCALE
1 0 1 2 3 4 5 6 7 8 9 10
20 Fe



DOCK, LONDON.
SECTIONS
H. W.
L. W.

# GREAT GRIMSB

Fig. 1.
ELEVATION

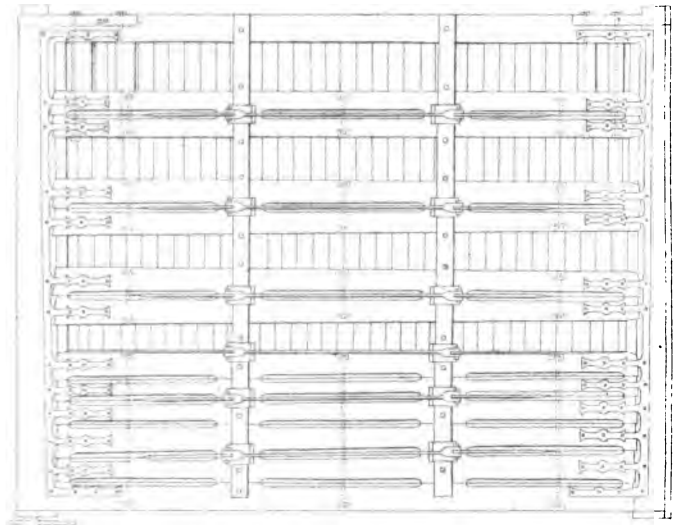
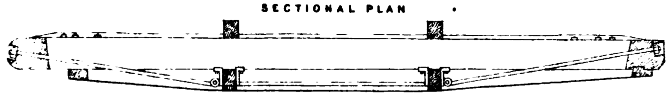


Fig. 5.
SECTIONAL PLAN



SCALE

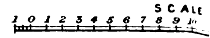



Fig. 10.

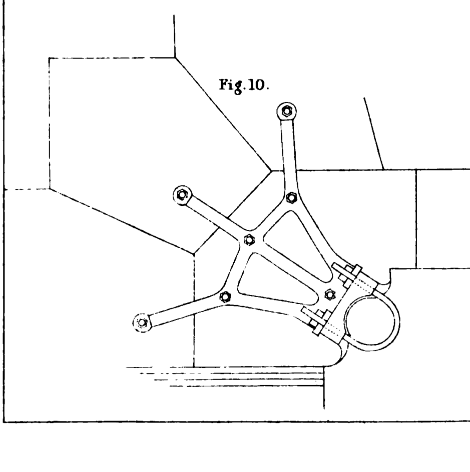
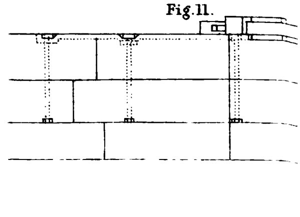
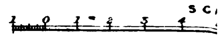


Fig. 11.



SC



T GRIMSBY.

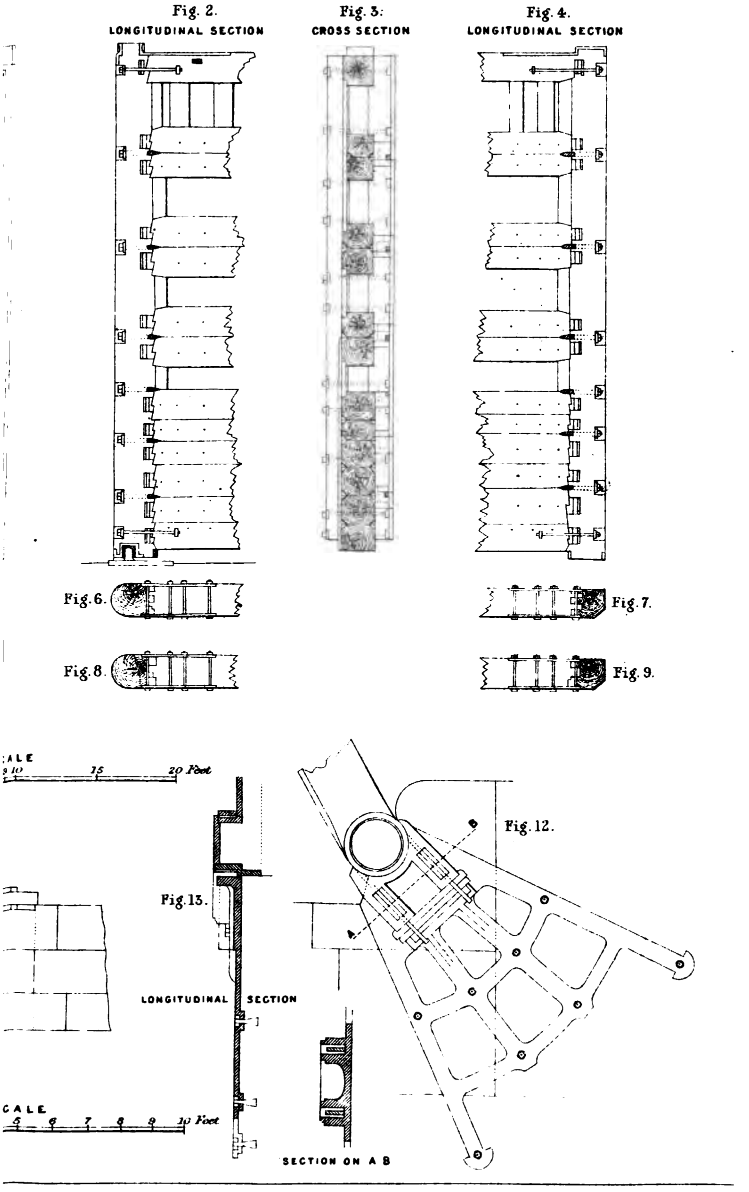
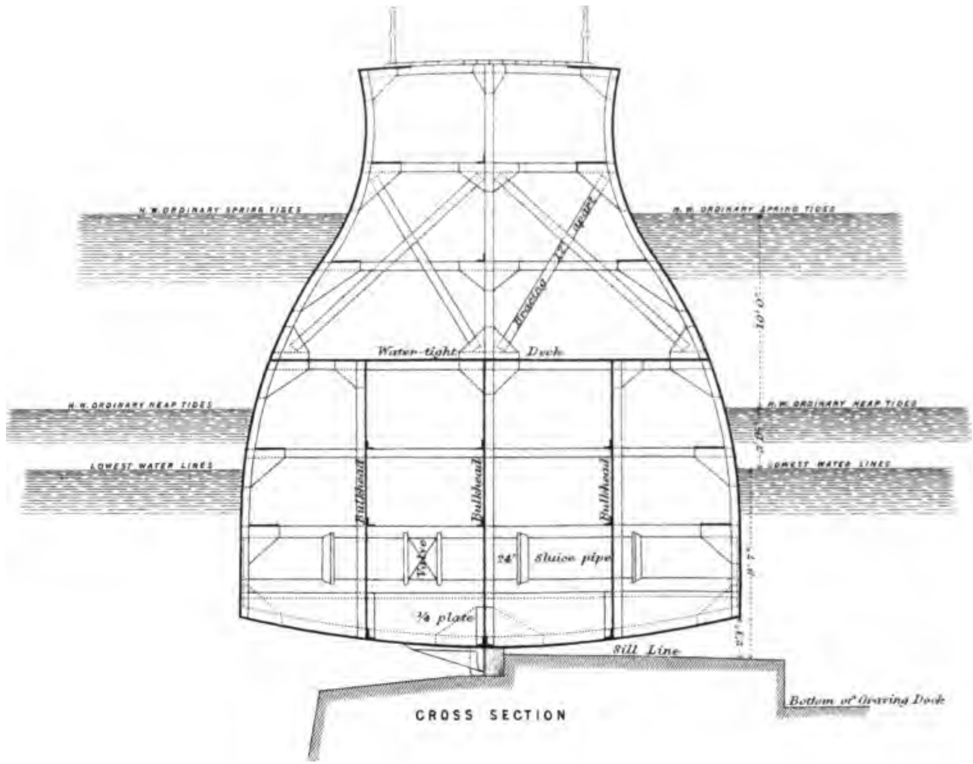
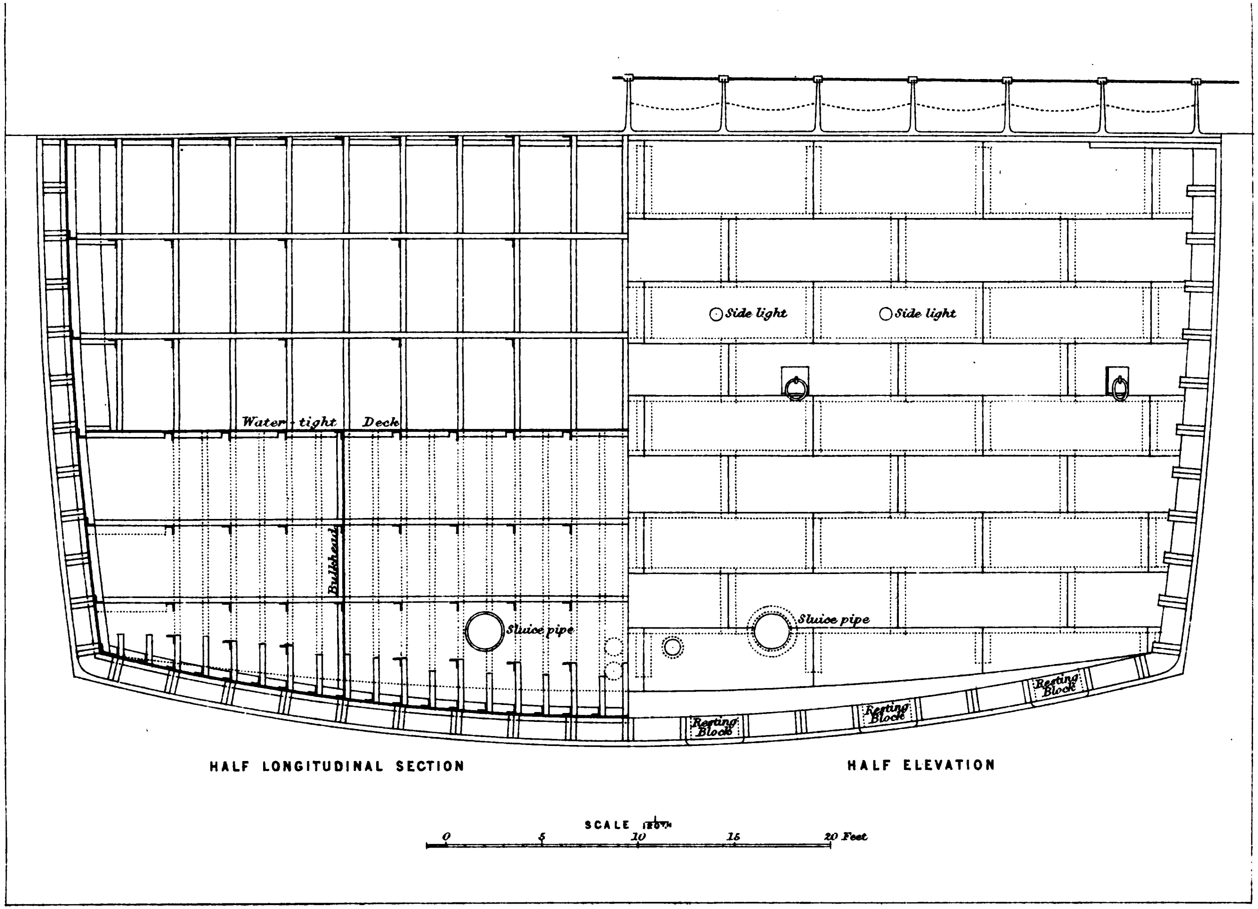


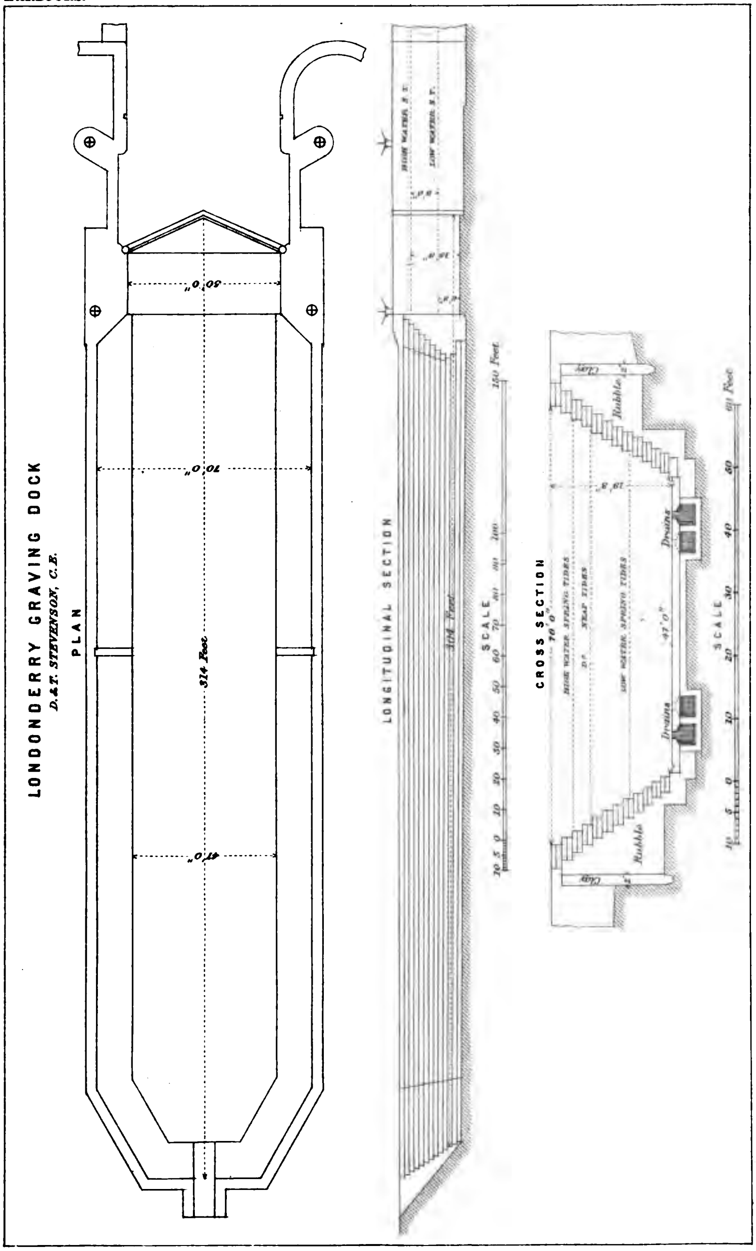
Fig. 2.
LONGITUDINAL SECTION
Fig. 3.
CROSS SECTION
Fig. 4.
LONGITUDINAL SECTION
Fig. 6.
Fig. 7.
Fig. 8.
Fig. 9.
:ALE
9 10 15 20 Feet
Fig. 12.
Fig. 13.
LONGITUDINAL SECTION
CALE
5 6 7 8 9 10 Feet
SECTION ON A B

# CARDIFF DOCKS

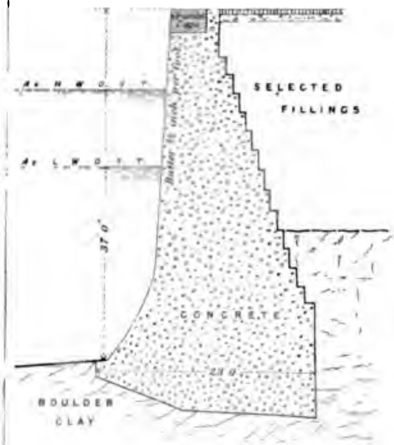
## CAISSON FOR GRAVING DOCK



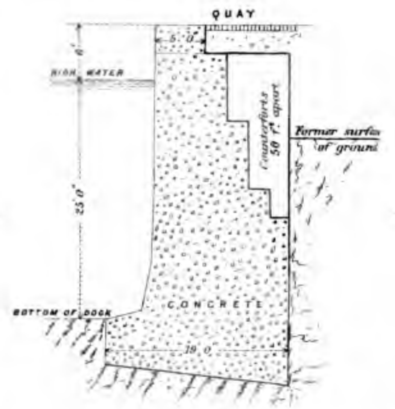

Water-tight Deck
Bulkhead
Sluice pipe
Side light
Side light
Sluice pipe
Resting Block
Resting Block
Resting Block
HALF LONGITUDINAL SECTION
HALF ELEVATION
SCALE 1/80th
0
5
10
15
20 Feet


LONDONDERRY GRAVING DOCK
D. & T. STEVENSON, C.E.
PLAN
50' 0"
70' 0"
314 Feet
47' 0"
LONGITUDINAL SECTION
HIGH WATER S.T.
LOW WATER S.T.
314 Feet
SCALE
150 Feet
CROSS SECTION
70' 0"
HIGH WATER SPRING TIDES
NEAP TIDES
LOW WATER SPRING TIDES
47' 0"
Drains
Drains
Rubble
Rubble
Clay
Clay
SCALE
60 Feet

LIVERPOOL, HORNBY DOCK
*G. F. LYSTER, C. E.*

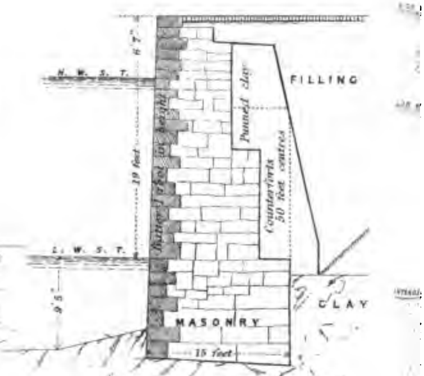



LONDON, ROYAL ALBERT DOCK
*A. M. RENDEL, C. E.*



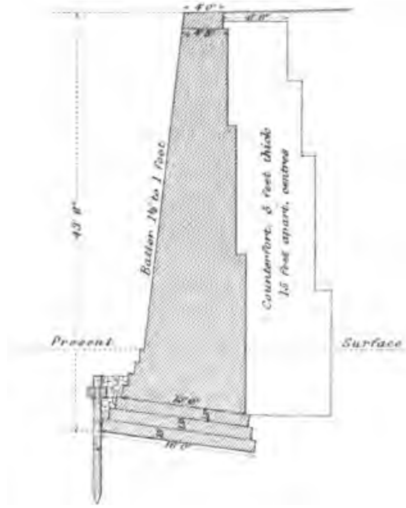

LIVERPOOL, LANGTON DOCK
*G. F. LYSTER, C. E.*


LEITH, EDINBURGH DOCK
*A. M. RENDEL & G. ROBERTSON, C. E.*



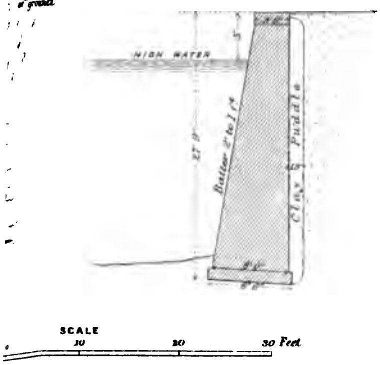
## MORECAMBE QUAY

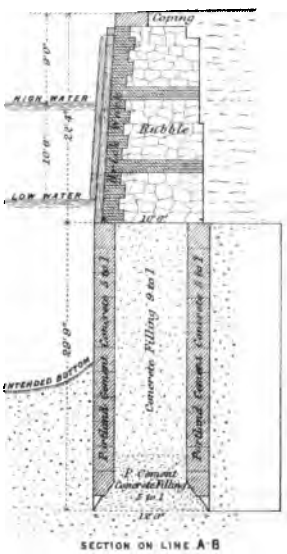
*D. & T. STEVENSON & R. SMALLMAN, C.E.*




## GLASSON DOCK

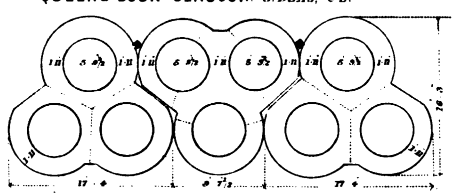
*D. & T. STEVENSON, C.E.*



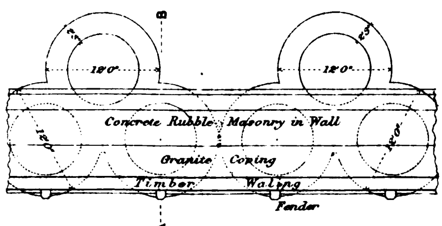

SECTION ON LINE A-B

## PLAN OF CYLINDERS AS CONSTRUCTED AT QUEEN'S DOCK GLASGOW. *J. DEAS, C.E.*




## PLANTATION QUAY, GLASGOW

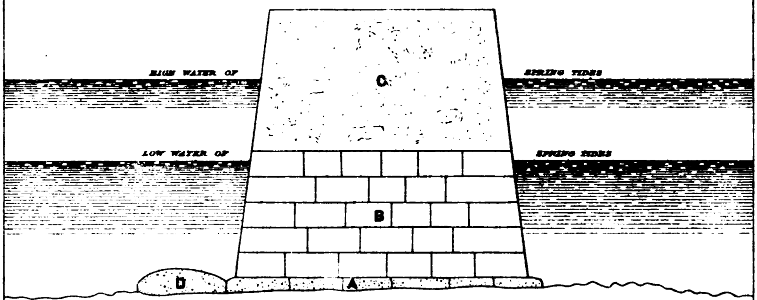
*J. DEAS, C.E.*




PLAN

## SOUTH BREAKWATER, ABERDEEN

*W. D. CAY, C.E.*

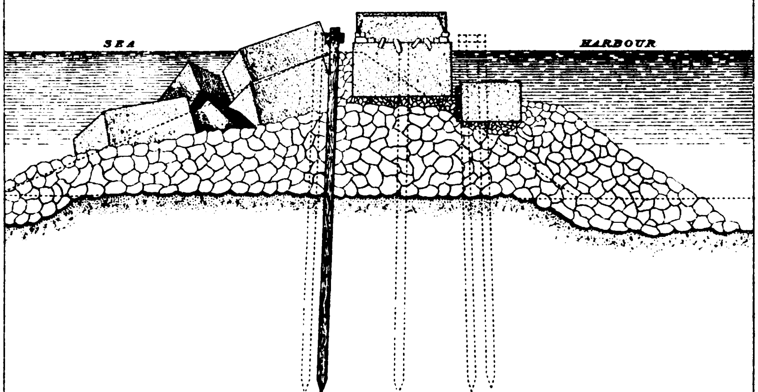



SCALE

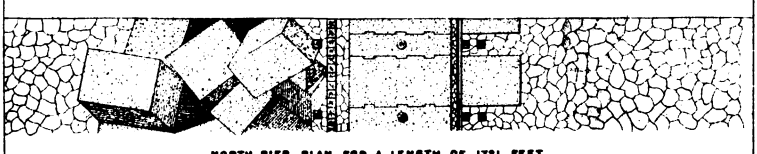
10 0 10 20 30 40 50 Feet

## DELTA OF THE DANUBE

*SIR CHARLES HARTLEY, C.E.*




NORTH PIER, CROSS SECTION FOR A LENGTH OF 1721 FEET.

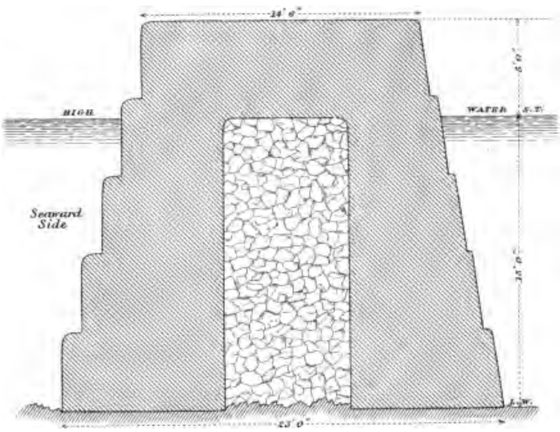


NORTH PIER, PLAN FOR A LENGTH OF 1721 FEET.

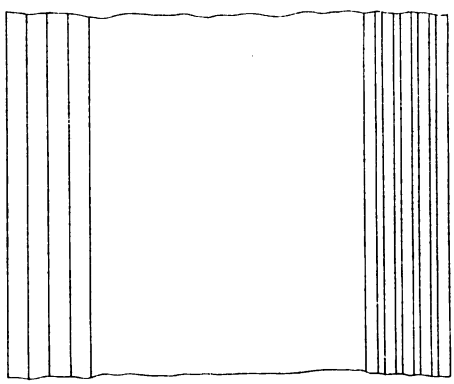
SCALE

10 5 0 10 20 30 Feet

# ANSTRUTHER BREAKWATER

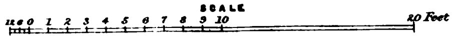


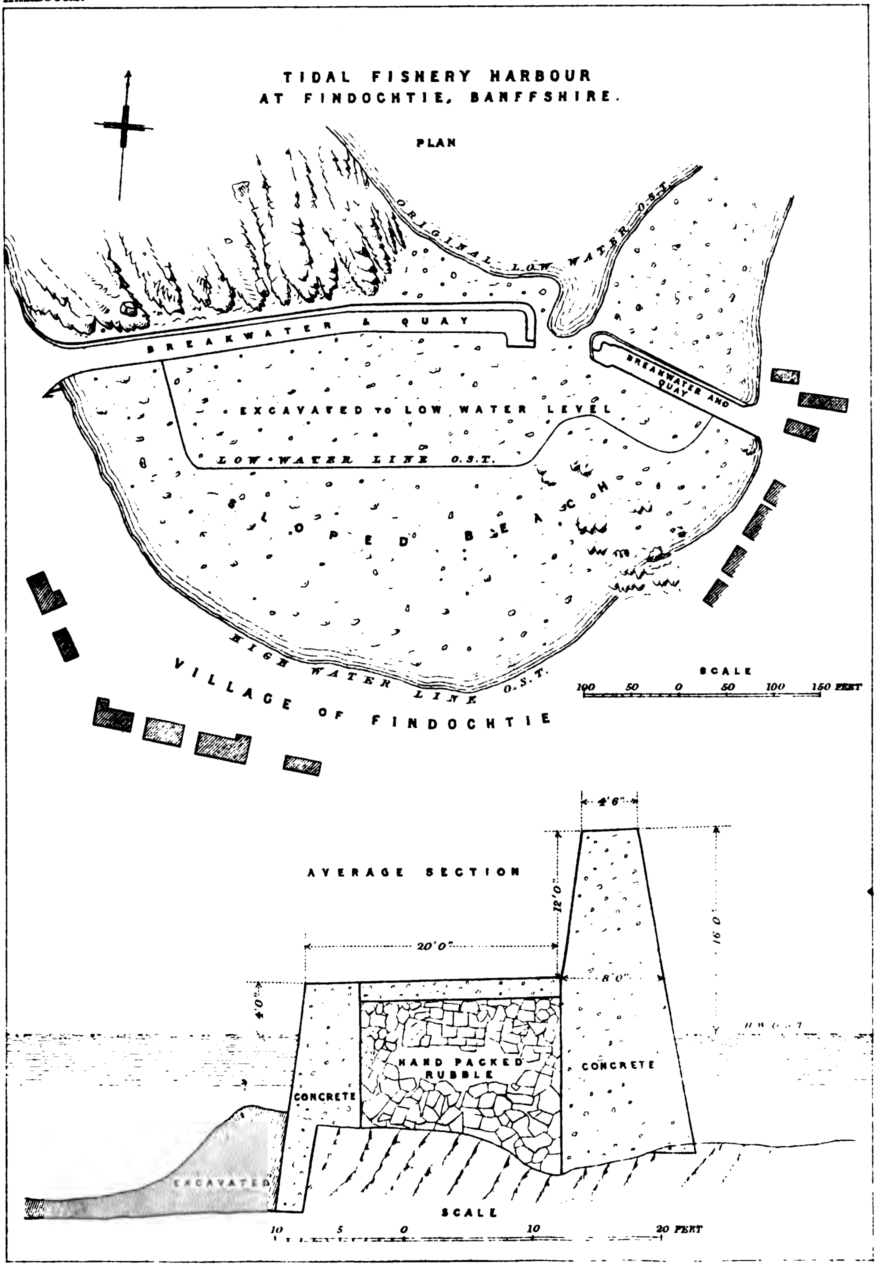

VERTICAL SECTION.

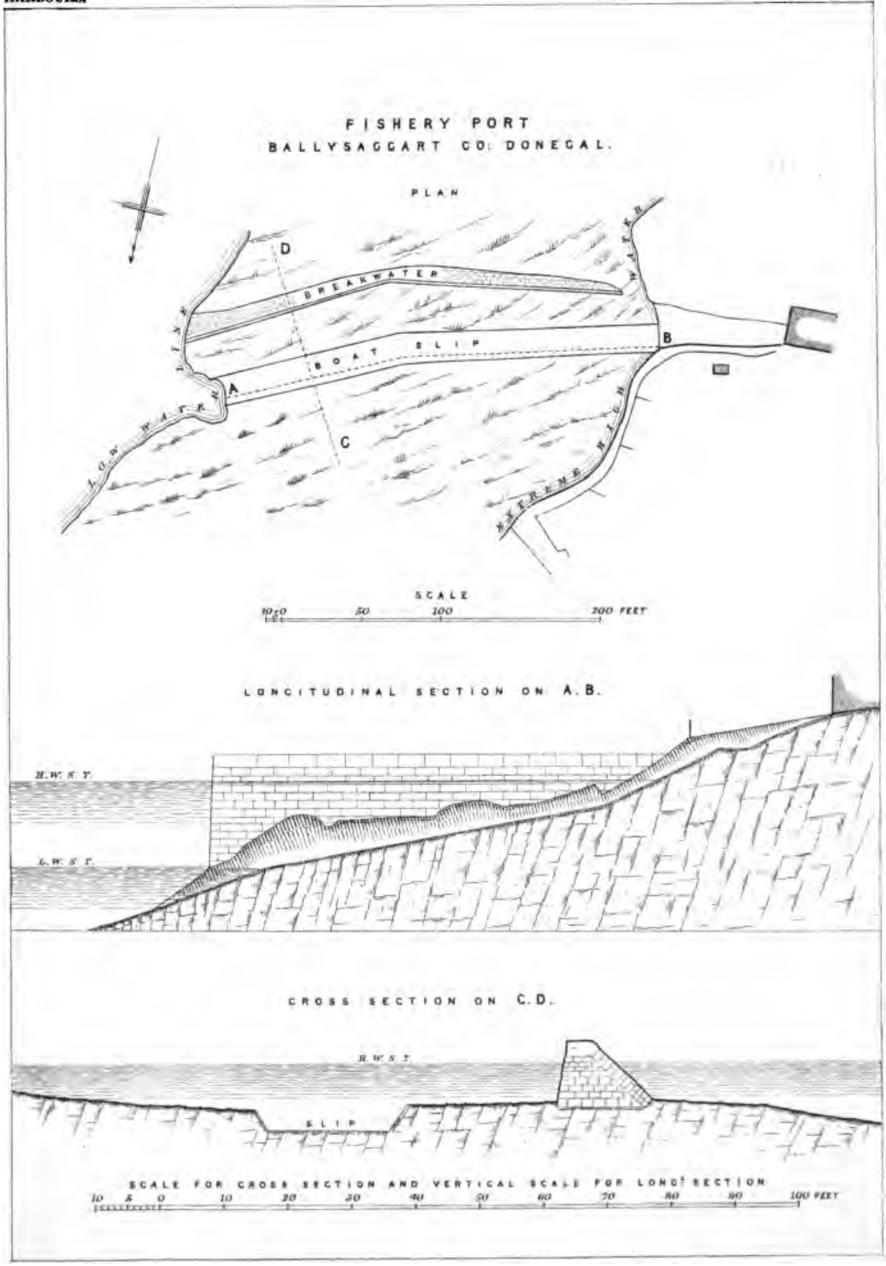


PLAN.

SCALE

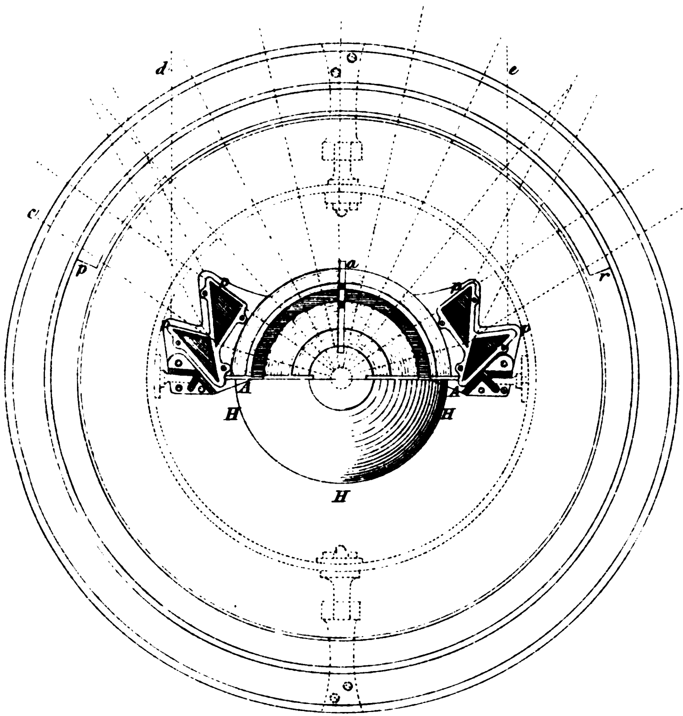



TIDAL FISHERY HARBOUR
AT FINDOCHTIE, BANFFSHIRE.
PLAN
ORIGINAL LOW WATER O.S.T.
BREAKWATER & QUAY
BREAKWATER AND QUAY
EXCAVATED TO LOW WATER LEVEL
LOW WATER LINE O.S.T.
SLOPED BEACH
HIGH WATER LINE O.S.T.
VILLAGE OF FINDOCHTIE
SCALE
100 50 0 50 100 150 FEET
AVERAGE SECTION
4'6"
12'0"
16'0"
20'0"
8'0"
4'0"
HAND PACKED RUBBLE
CONCRETE
CONCRETE
EXCAVATED
SCALE
10 5 0 10 20 FEET

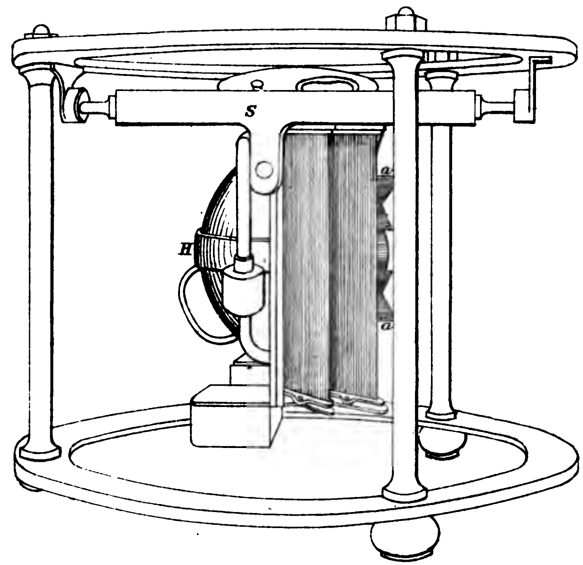

FISHERY PORT
BALLYSAGGART CO: DONEGAL.
PLAN
D
BREAKWATER
BOAT SLIP
LOW WATER LINE
A
B
C
EXTREME HIGH WATER
SCALE
10 5 0 50 100 200 FEET
LONGITUDINAL SECTION ON A.B.
H.W.S.T.
L.W.S.T.
CROSS SECTION ON C.D.
H.W.S.T.
SLIP
SCALE FOR CROSS SECTION AND VERTICAL SCALE FOR LONG^L SECTION
10 5 0 10 20 30 40 50 60 70 80 90 100 FEET

# CONDENSING LIGHT FOR STEAMERS






MIDDLE HORIZONTAL SECTION




SIDE VIEW